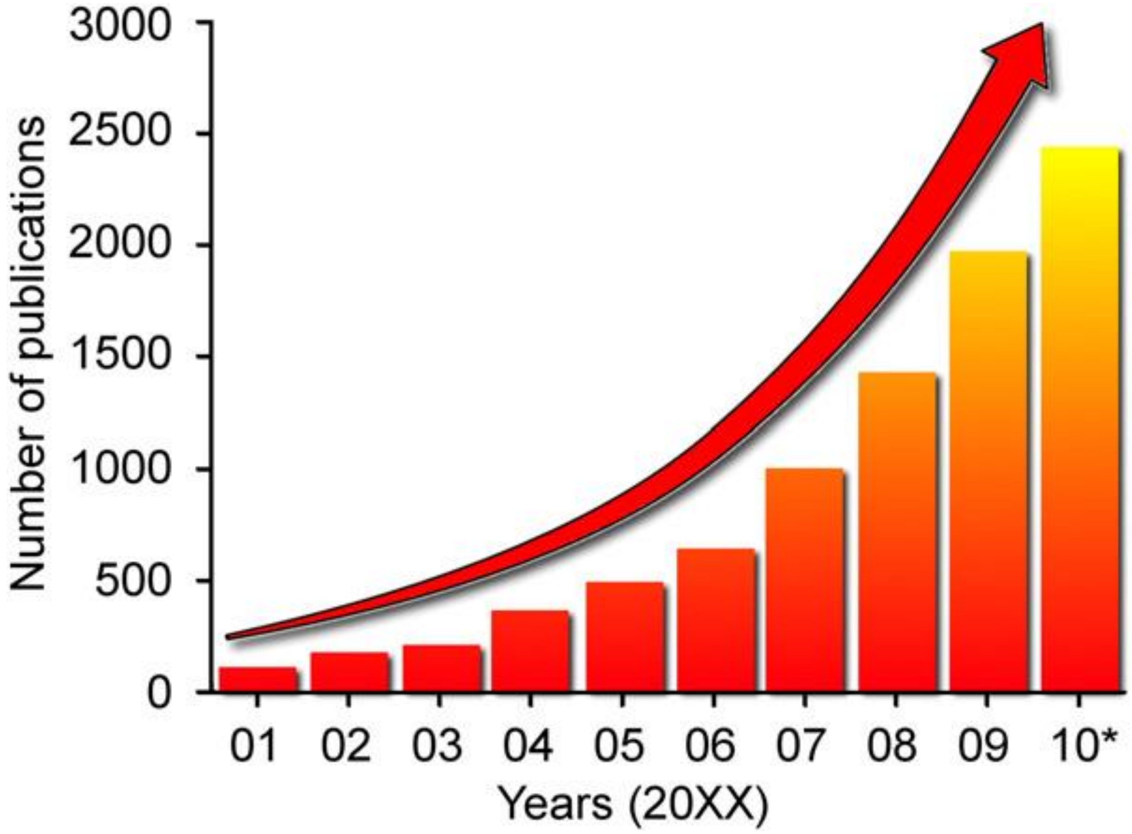
TOGETHER FOR BRIGHT FUTURE

Low Temp. Plasma

Prof. Mohammed Shihab

Physics Department

Nanotechnology



Han etal, J. Phys. D: Appl. Phys. **44** (2011) 174019

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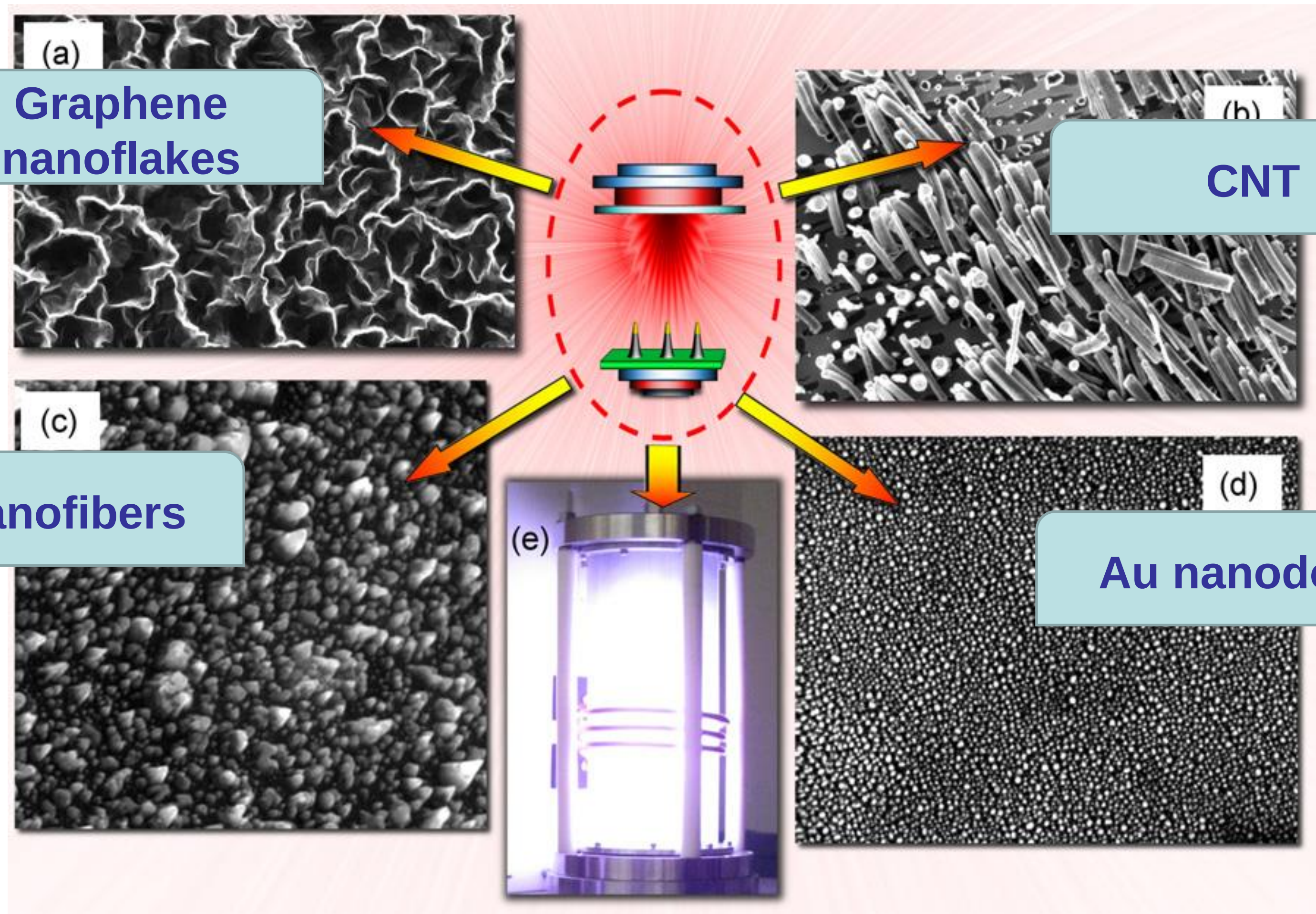
Plasma & Nanotechnology



Graphene nanoflakes

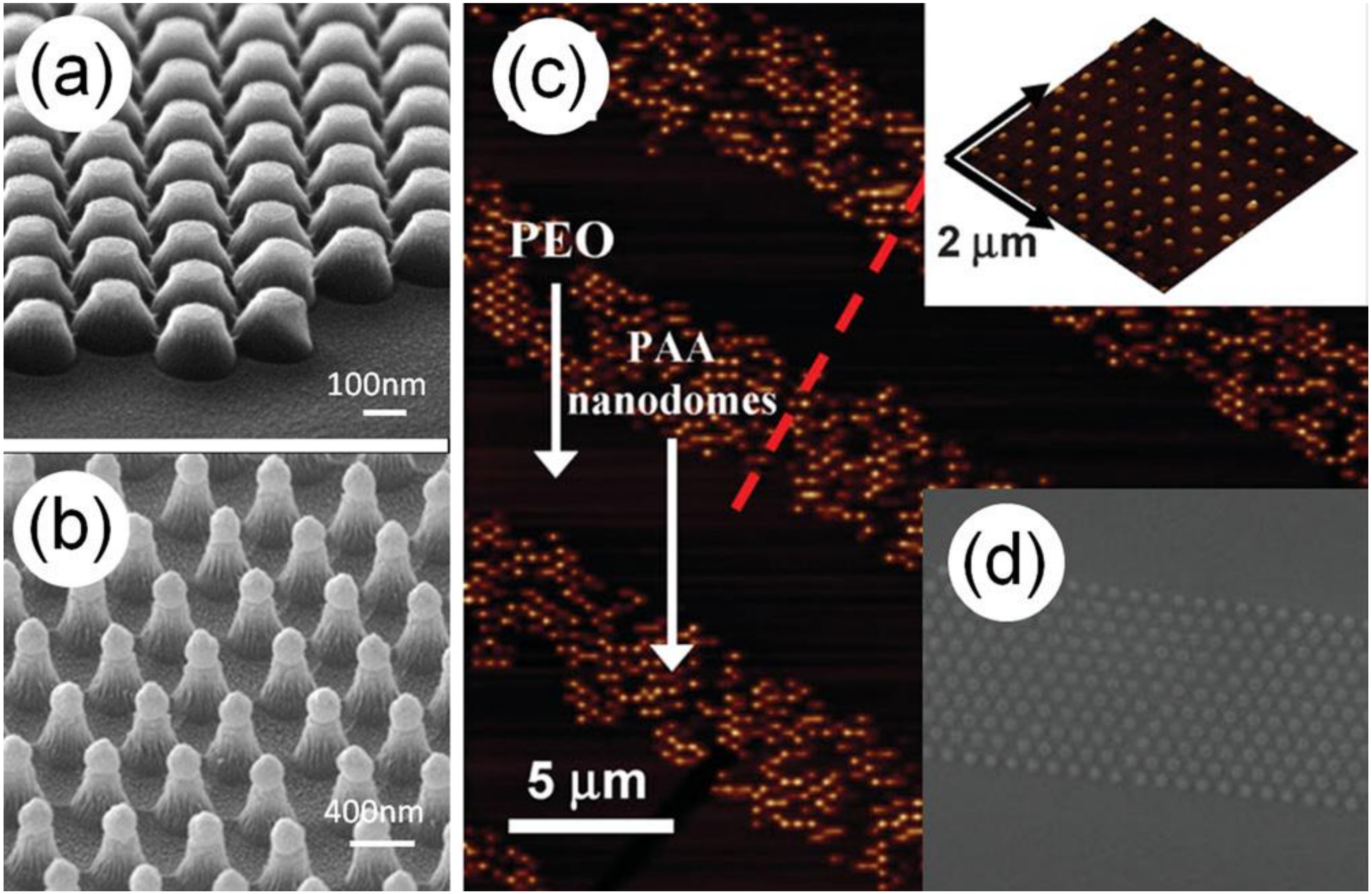
CNT

Si nanofibers

Au nanodots

Han etal, J. Phys. D: Appl. Phys. **44** (2011) 174019

Nano-Patterns



Ostrikov etal, J. Phys. D: Appl. Phys. **44** (2011) 174001

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Good and fast Start

- **References:**

- **PRINCIPLES OF PLASMA DISCHARGES AND MATERIALS PROCESSING, MICHAEL A. LIEBERMAN & ALLAN J. LICHTENBERG, John Wiley & Sons, Inc (2005).**

- **PHYSICS OF RADIO-FREQUENCY PLASMAS, PASCAL CHABERT & NICHOLAS BRAITHWAITE, Cambridge University Press (2011).**

- **Spacial issue „ Plasma and Nanotechnology" : , J. Phys. D: Appl. Phys. 44 (2011)**

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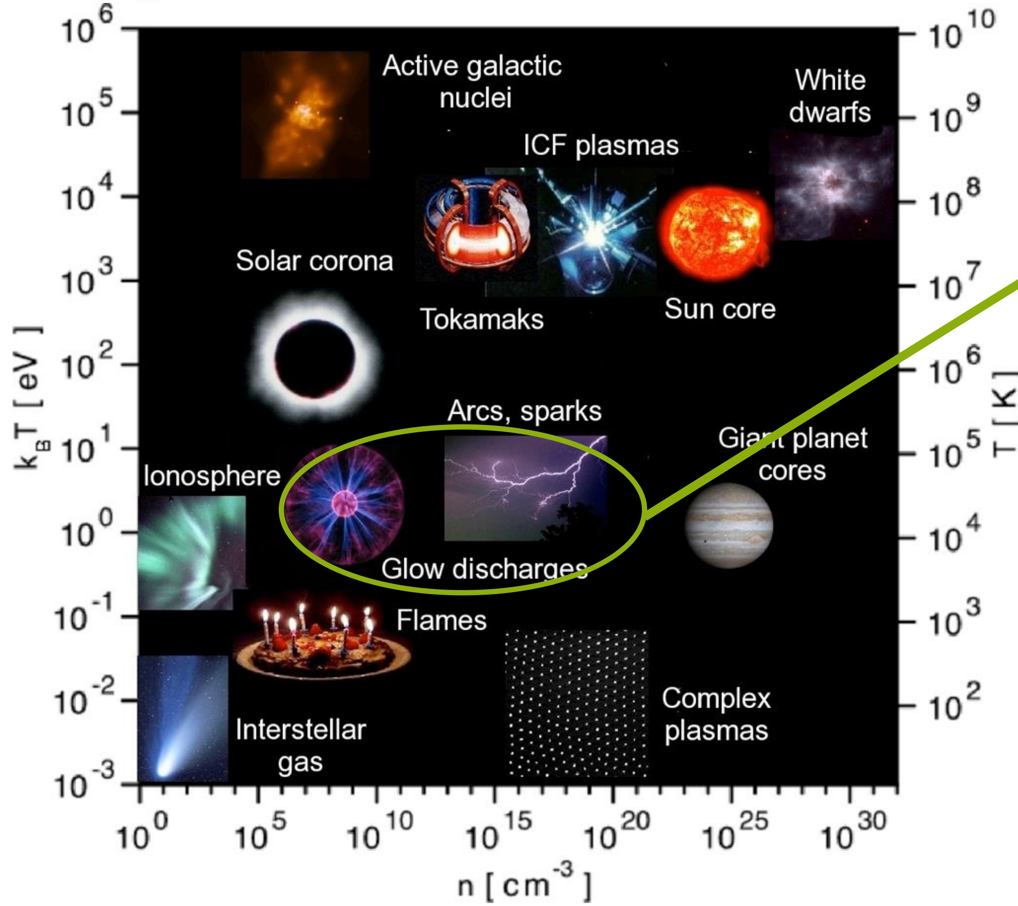
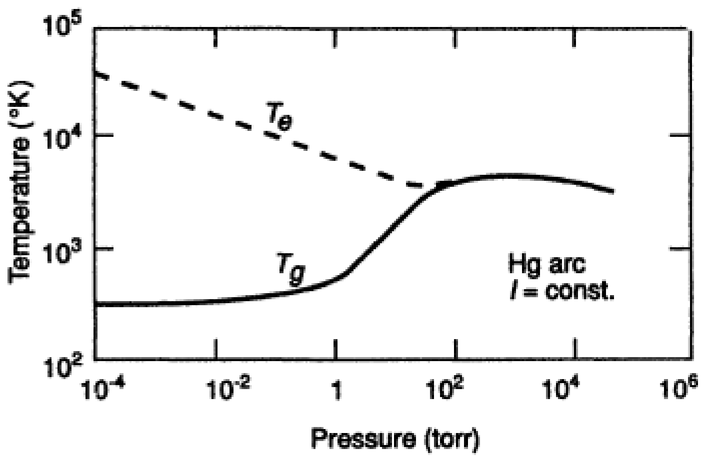
Low Temperature Plasma



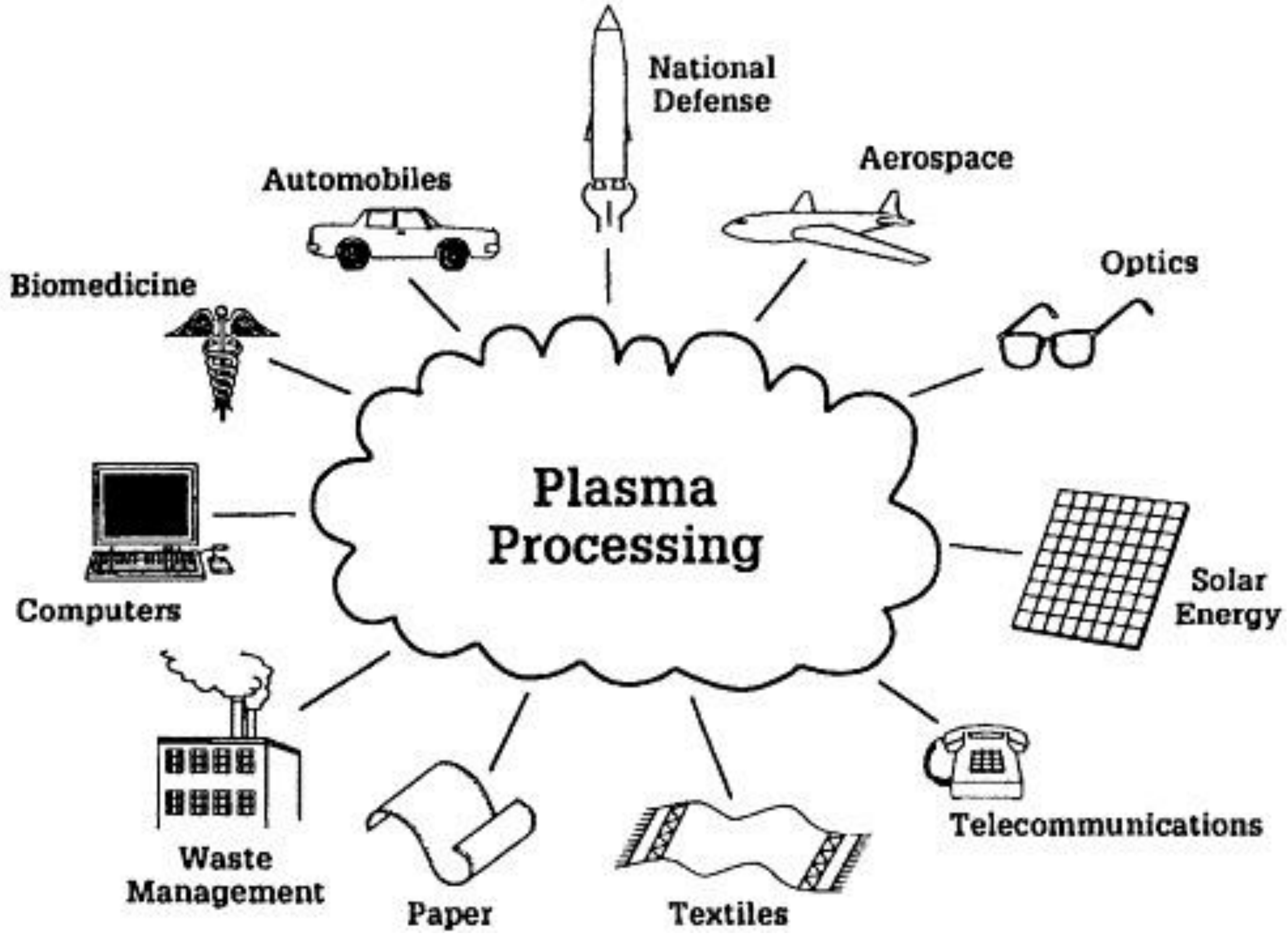
- Low degree of ionization
- Neutral background 10^6 the ion and electron density
- Collisions with the background gas is dominant compared to electron ion collisions



- Non-equilibrium plasmas at low pressures

$T_e = 11000 - 60000K$ $\quad T_e = 1 - 5eV \quad T_i = 300K$

Various applications



Is it really hot?

Does the ocean water temp. change?

$$\Delta Q = \text{Mass} \times \text{specific heat} \times \text{Temperature difference}$$

Plasma Chemistry I

- **Dissociation of feedstock gas into active neutral free radicals:**

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

$$e^- + CF_4 \rightarrow CF_2 + 2F + e^-$$

$$e^- + CF_4 \rightarrow CF + F_2 + F + e^-$$

- **Dissociation of the free radicals**

$$e^- + CF_3 \rightarrow CF_2 + F + e^-$$

$$e^- + CF_2 \rightarrow CF + F + e^-$$

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Plasma Chemistry II

- **Dissociative ionization and attachment:**

$$e^- + CF_4 \rightarrow CF_3^+ + F + 2e^-$$

$$e^- + CF_4 \rightarrow CF_3^- + F$$

$$e^- + CF_4 \rightarrow CF_3 + F^-$$

- **Chlorine discharge**

$$e^- + Cl_2 \rightarrow Cl_2^+ + 2e^-$$

$$e^- + Cl_2 \rightarrow Cl^+ + Cl + 2e^-$$

Plasma Chemistry III

- **Chemical reactions between neutrals in the presence of a third body**

$$CF_3 + F + M \rightarrow CF_4 + M$$
$$CF_2 + F + M \rightarrow CF_3 + M$$
$$CF + F + M \rightarrow CF_2 + M$$

- **At the substrate**
- **Removing**

$$Cl(g) + Cl(ads) \rightarrow Cl_2(g)$$

- **Etching**

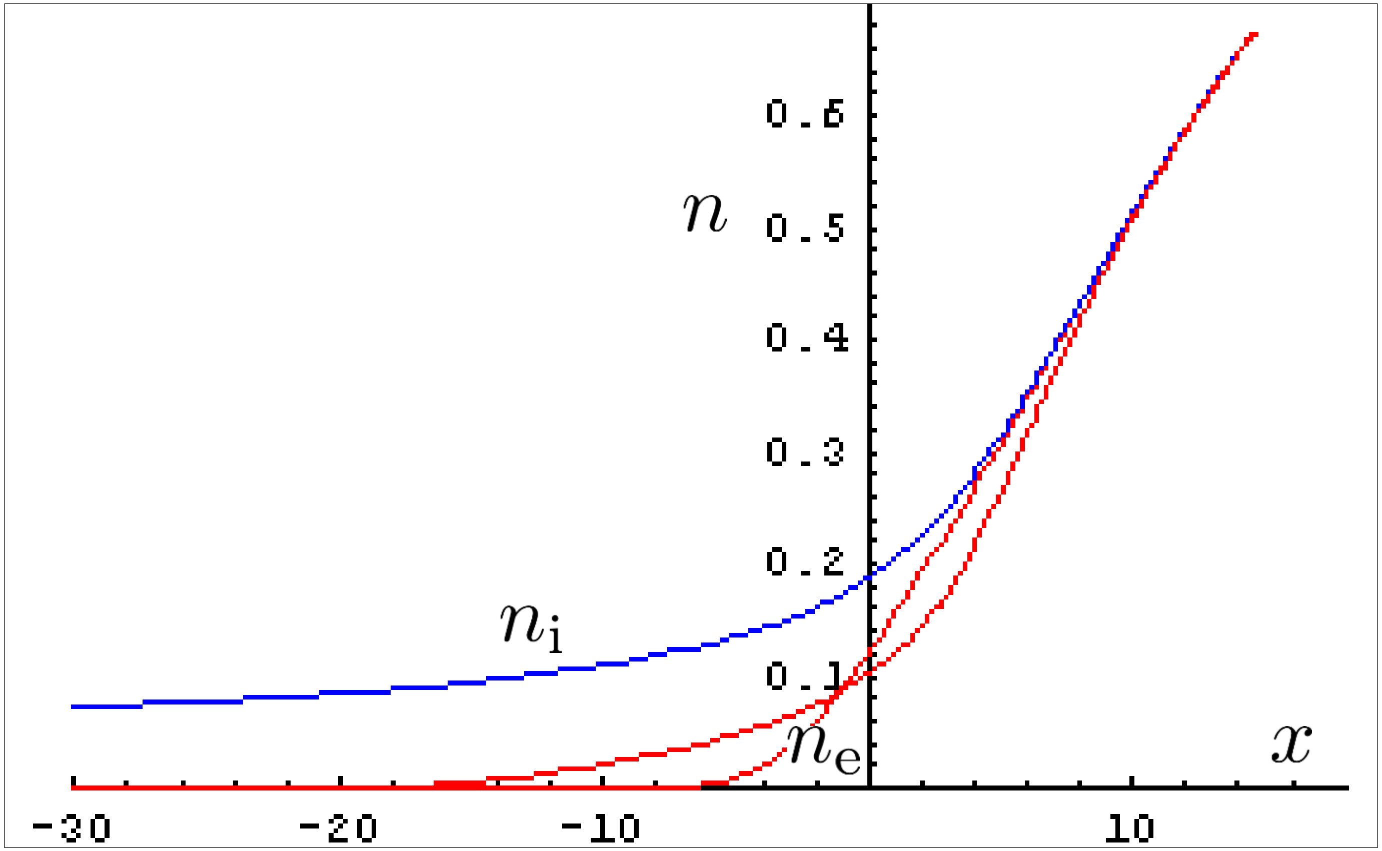
$$Cl(g) + SiCl_3(s) \rightarrow SiCl_4(g)\uparrow$$

- **Deposition or growth**

$$SiH(g) \rightarrow Si(s)\downarrow + H(g)\uparrow$$

Plasma Sheaths

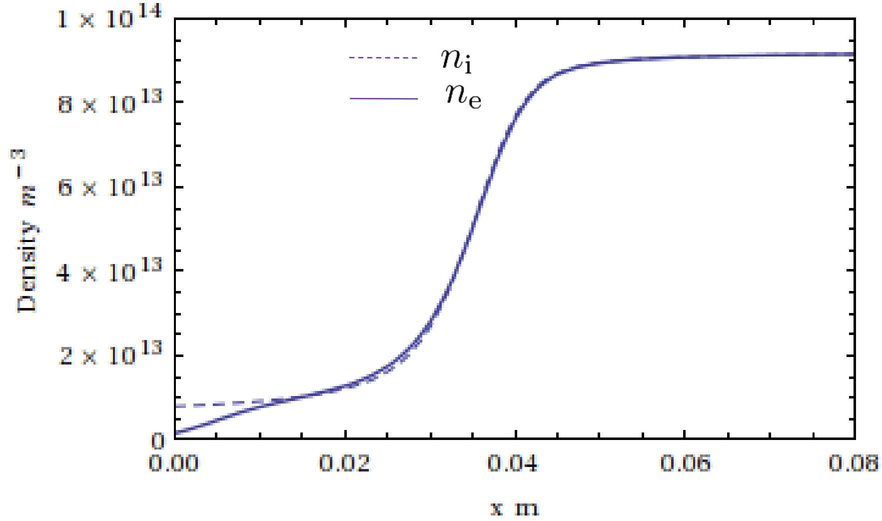
$$\omega_{\rm pe} \gg \omega_{\rm RF} \gg \omega_{\rm pi}$$

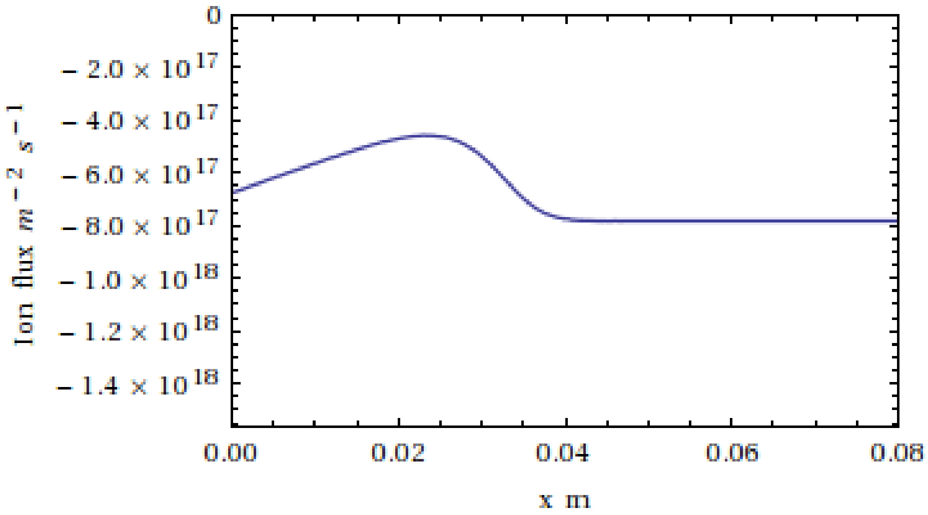


Ion Dynamics

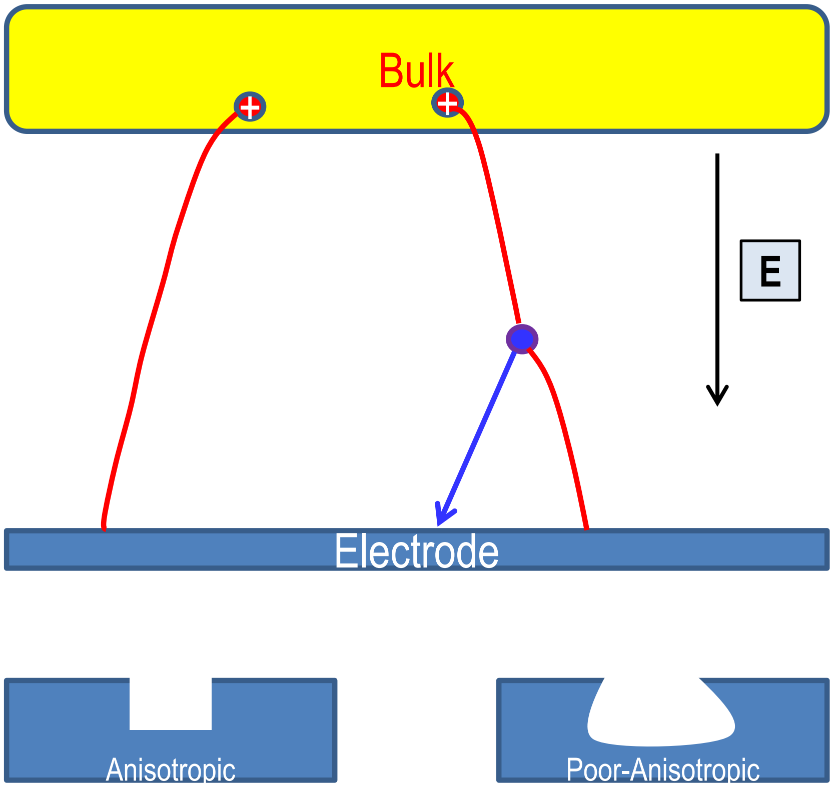
- The intermediate regime

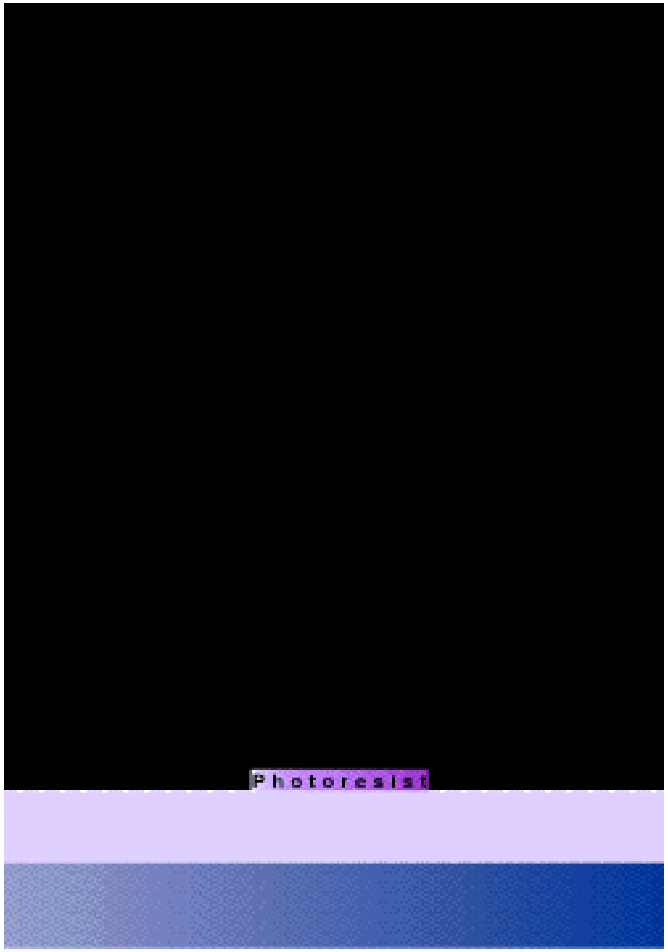
$$\omega_{\mathrm{RF}} \approx \omega_{\mathrm{pi}}$$





Plasma Processing



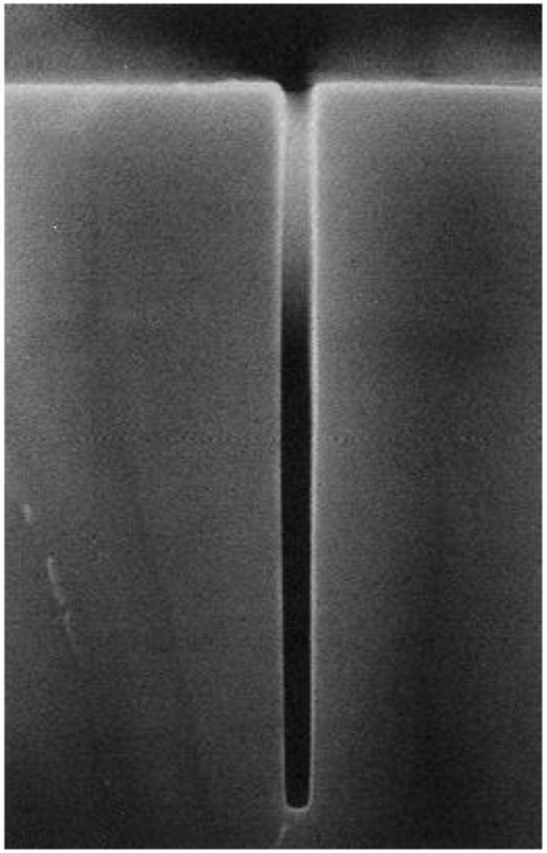


Intel

Plasma Etching

- **An etched profile with**
  - **0.5 micrometer (500 Nanometer) wide**
  - **4 micrometer (4000 nanometer)**
- **Such profiles are used for device isolation and charge storage capacitores.**

- **Human hair is 50-100 micrometer in diameter.**



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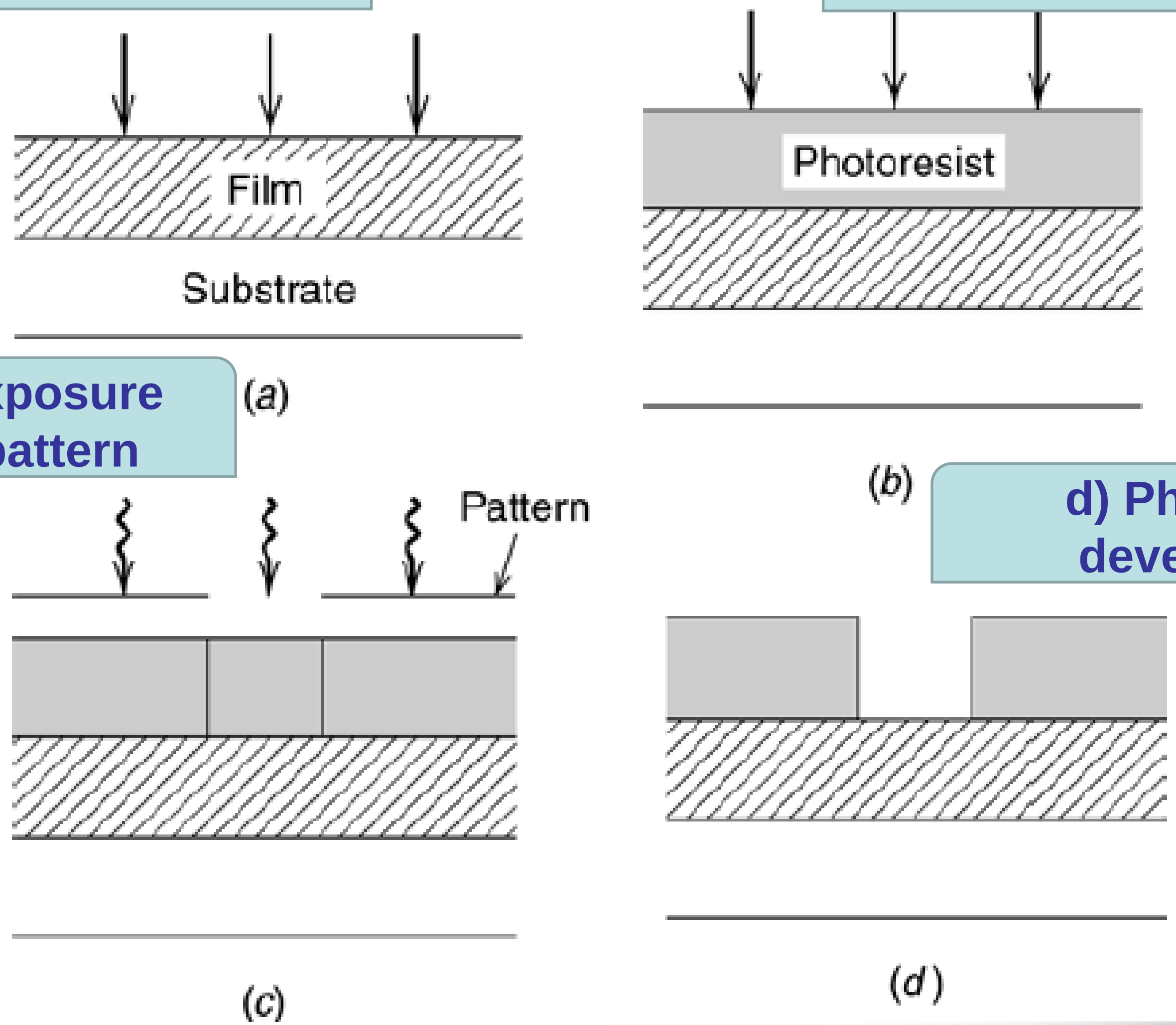
Plasma Etching steps I

a) Metal Deposition

b) Photoresist deposition

c) Optical exposure through a pattern

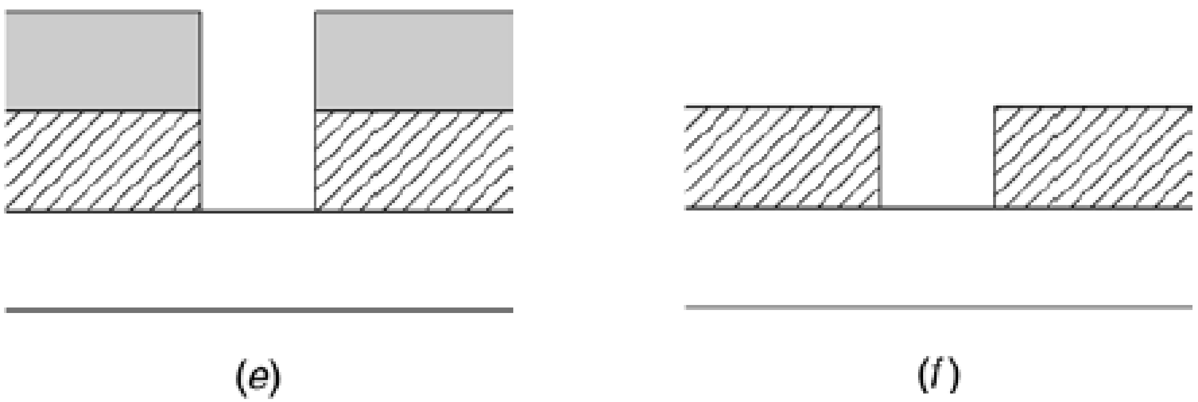
d) Photoresist development



Plasma Etching steps II

e) Anisotropic etching

f) Photoresist removal



- **Process Selectivity:**
  - **Depends on the plasma species**
  - **Energy threshold & energy activation**

Wet and Dry etching

- **Carbon Floride (CF4) does not react with Silicin (Si).**

- **Dissociative ionization and attachment:**

$$e^- + CF_4 \rightarrow CF_3^+ + F + 2e^-$$

$$e^- + CF_4 \rightarrow CF_3^- + F$$

$$e^- + CF_3 \rightarrow CF_3 + F^-$$

- **Wet etching**

$$\mathrm{Si}(s) + 4\mathrm{F}(g) \rightarrow \mathrm{SiF}_4(g) \uparrow$$

- **Dry etching: Accelerate CF_3^+ toward the Silicon substrate**

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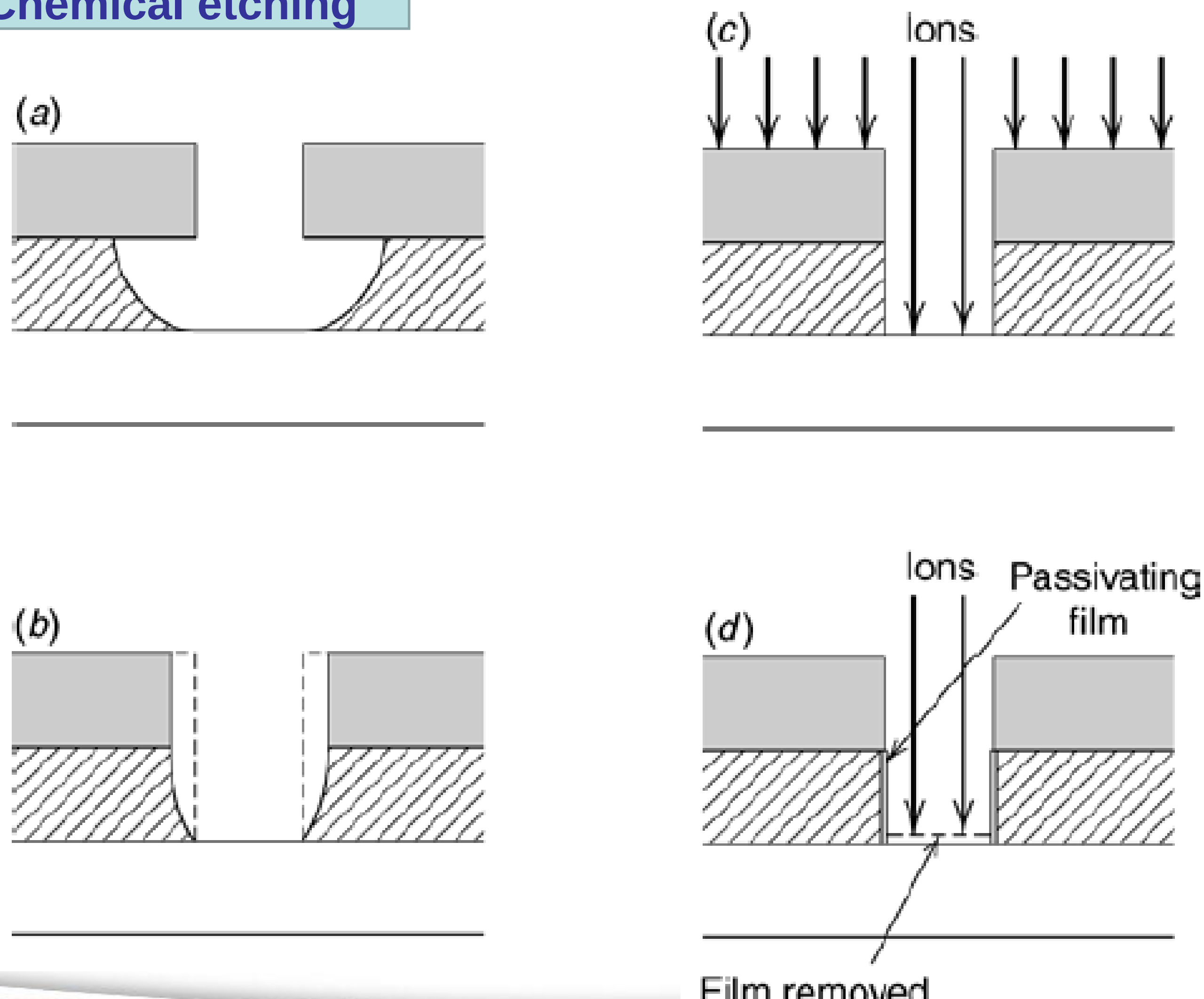
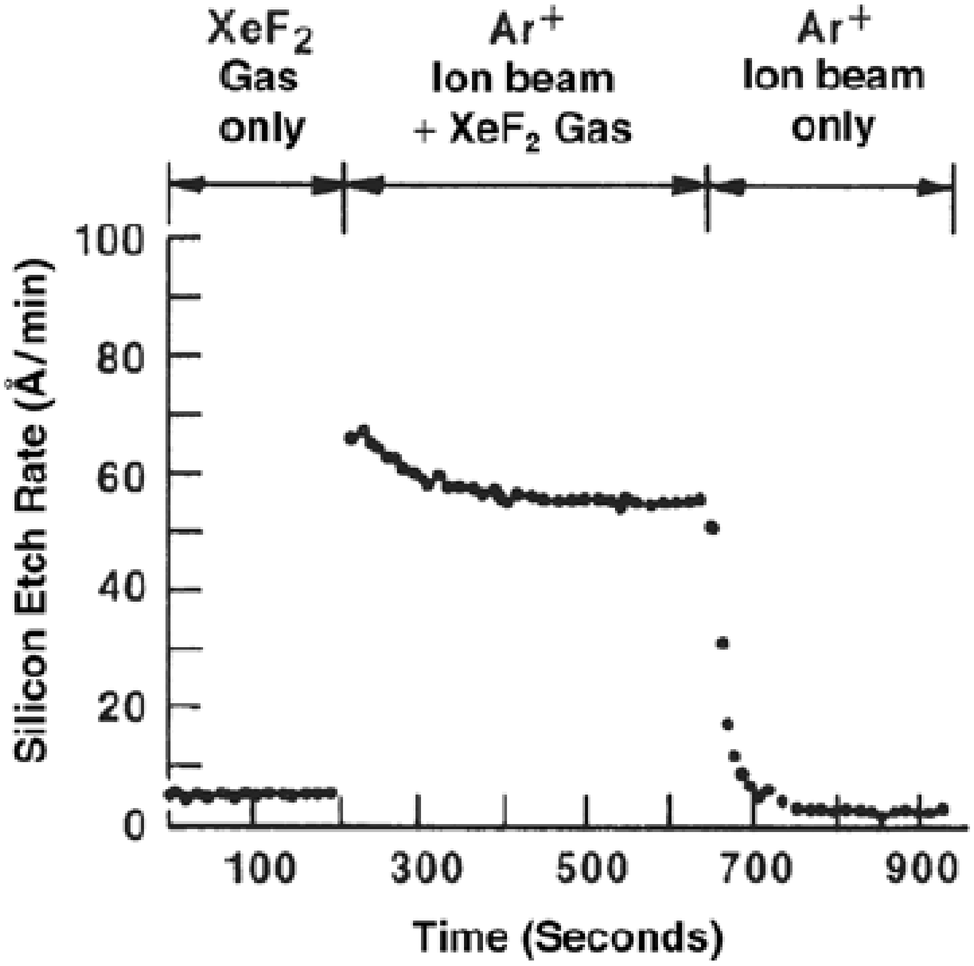
Plasma Etching steps II

Wet etching
Chemical etching

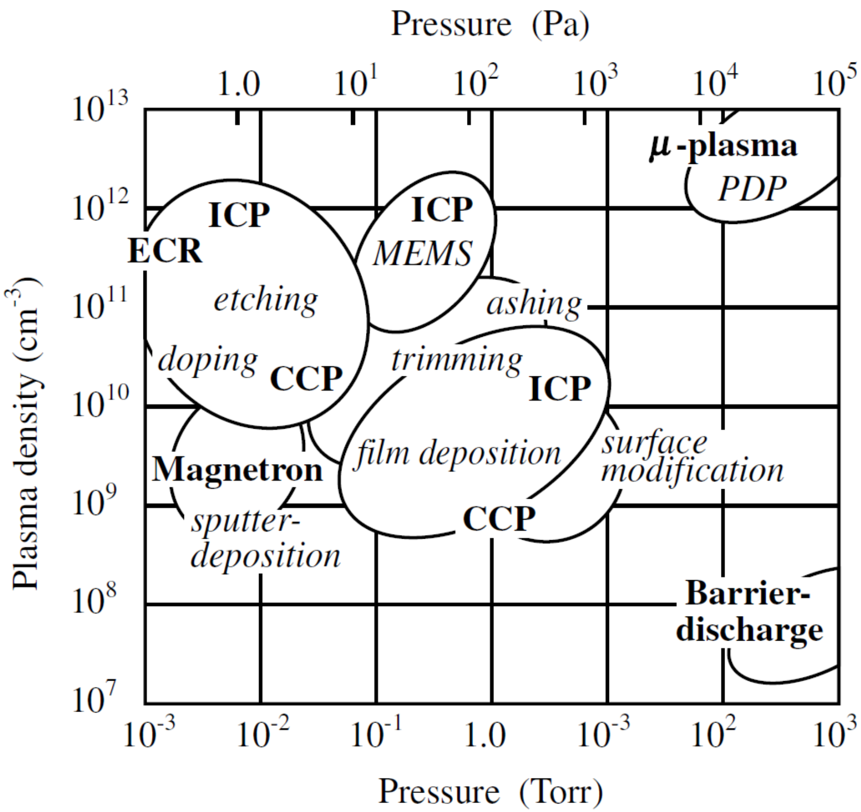
Dry etching



Ion enhanced plasma etching



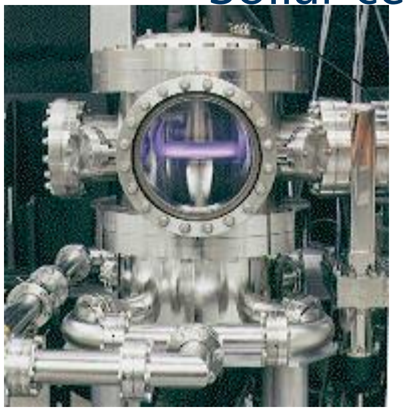
Devices

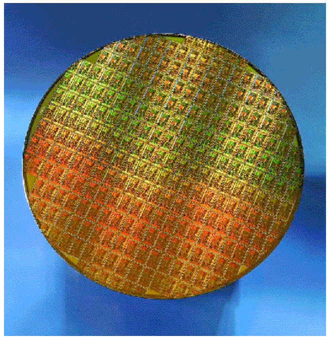


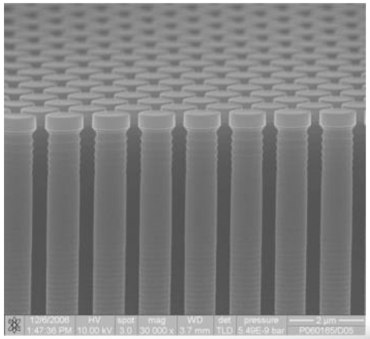
Plasma electronics,

Applications in Microelectronic Device Fabrication

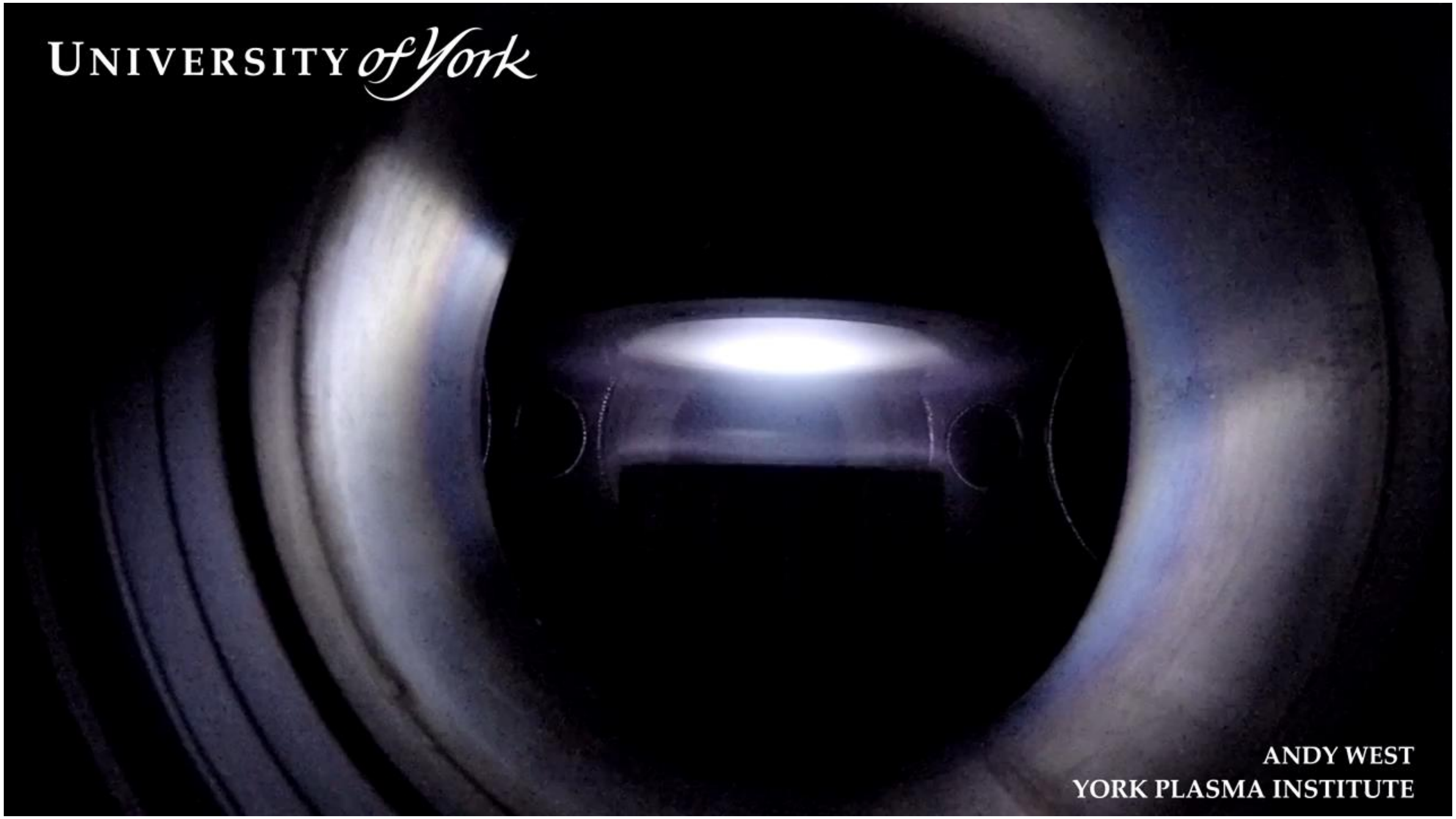
- **Capacitive coupled plasma** are used in plasma etching and deposition process for production of:
  - Integrated circuits
  - Sollar cells



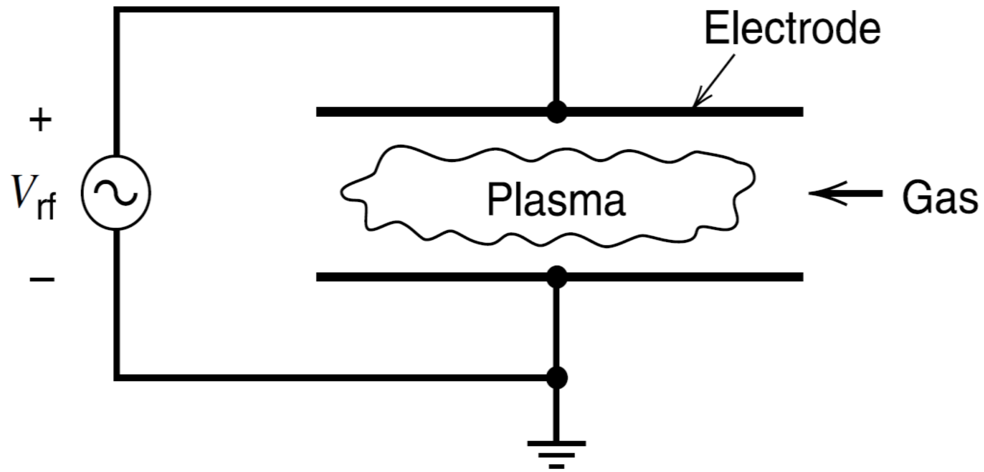


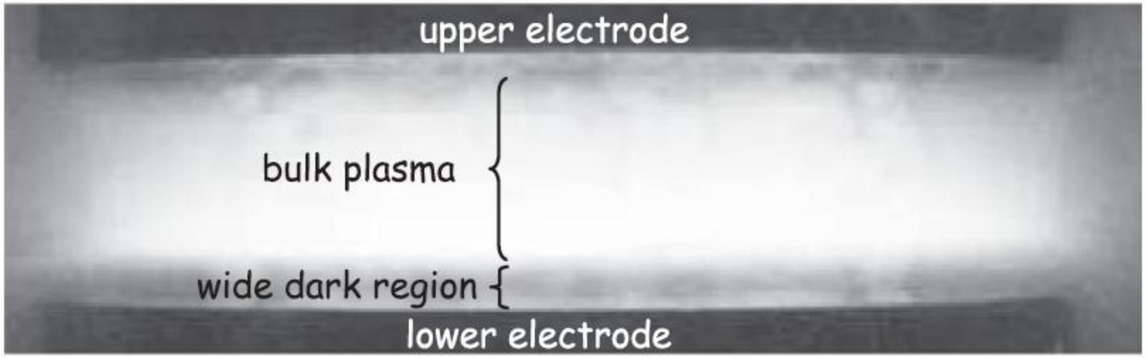


Capacitive coupled plasma



Symmetric discharge





- **The ion flux and the ion energies increase (decreases) by increasing (decreasing) the deriving frequency.**

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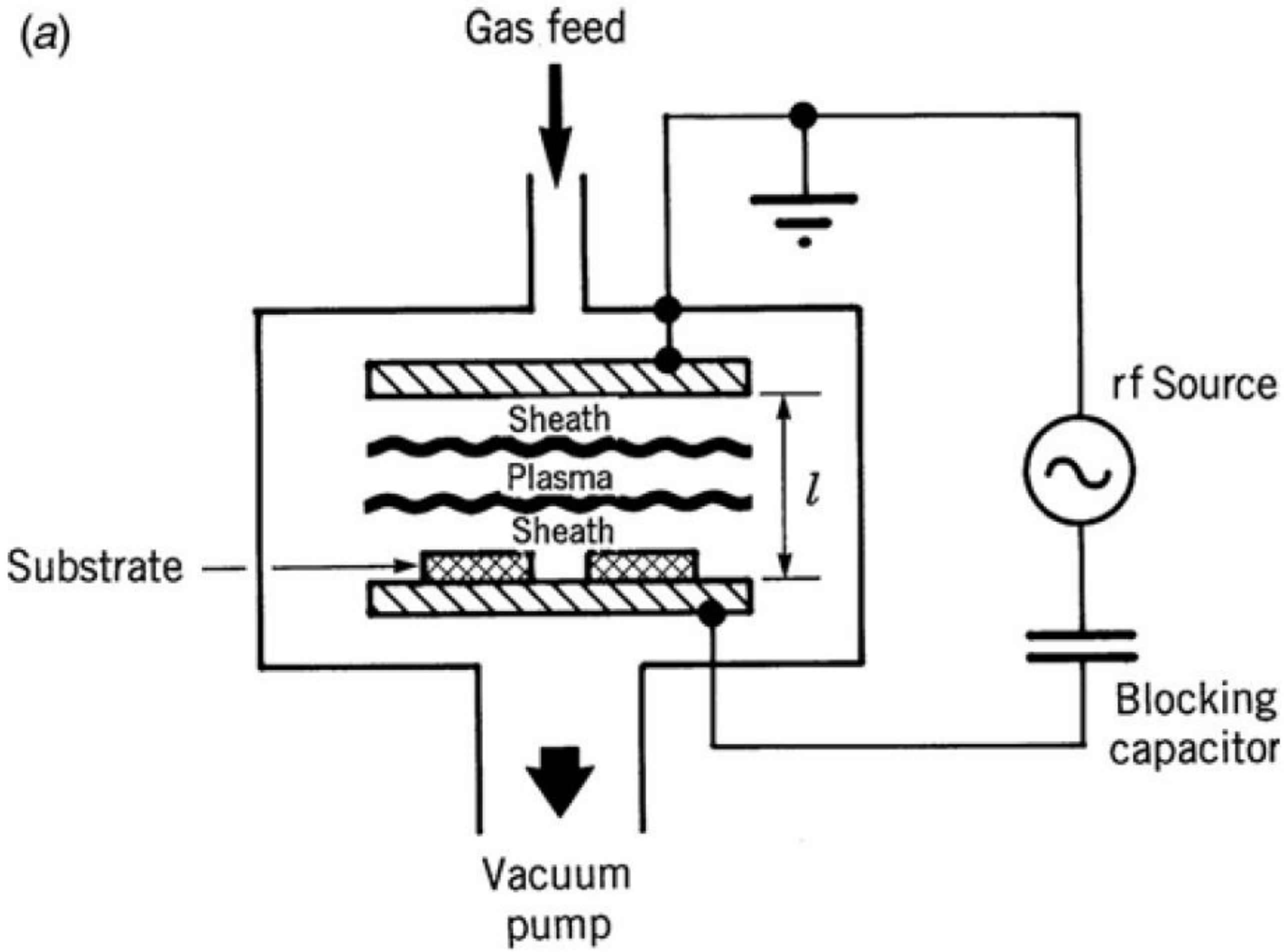
CCPs & blocking a Capacitor



Geometrically Asymmetric

- **The RF current is constant.**
- **But the ground electroge**

Area is greater then the powered electrode area.

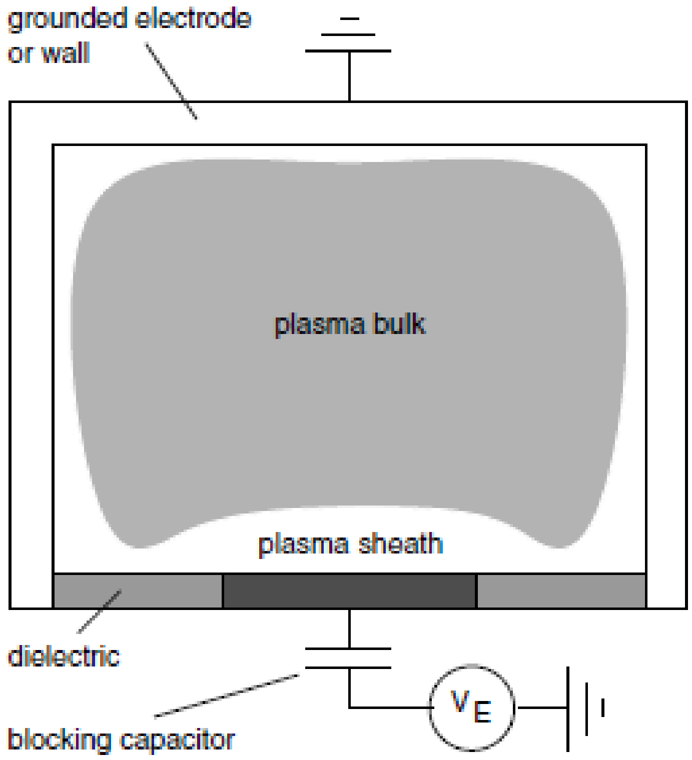
$$J_{\mathrm{g}} = I_{\mathrm{rf}}/A_g$$

$$J_{\mathrm{p}} = I_{\mathrm{rf}}/A_p$$

$$J_{\mathrm{p}} \gg J_{\mathrm{g}}$$

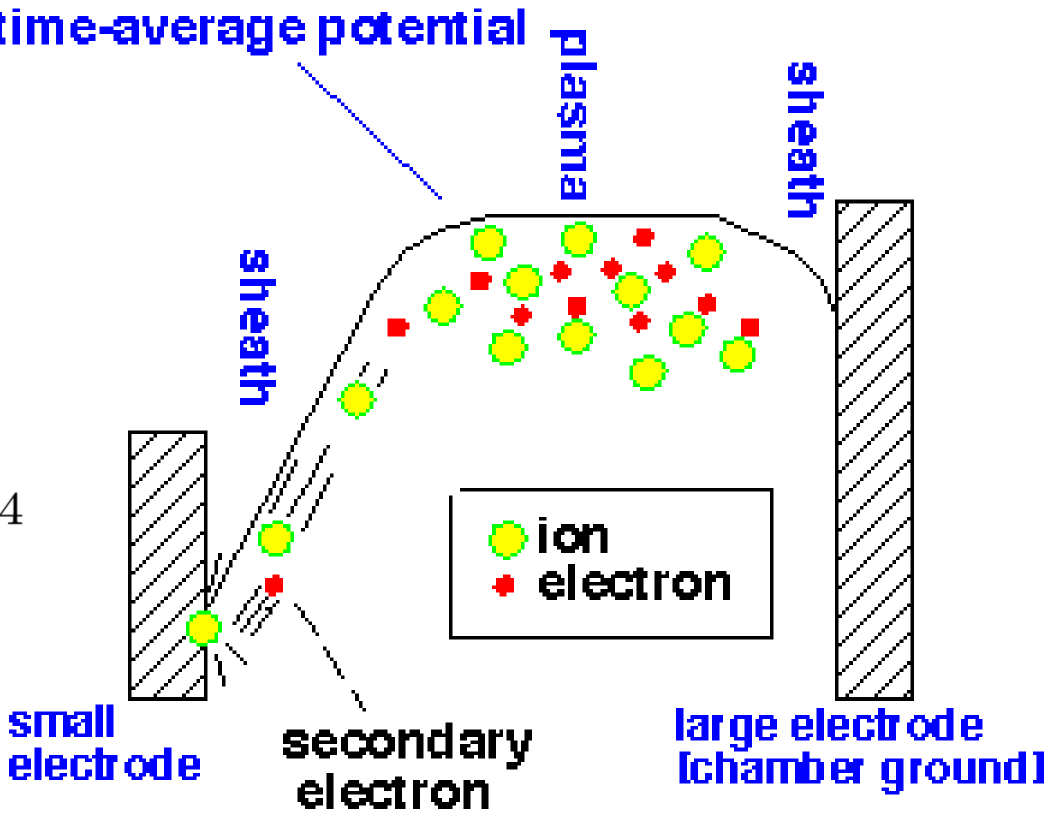
- The blocking capacitor blocks DC currents:

$$\frac{V_{\mathrm{p}}}{V_{\mathrm{g}}} = \left(\frac{A_{\mathrm{g}}}{A_{\mathrm{p}}}\right)^4$$



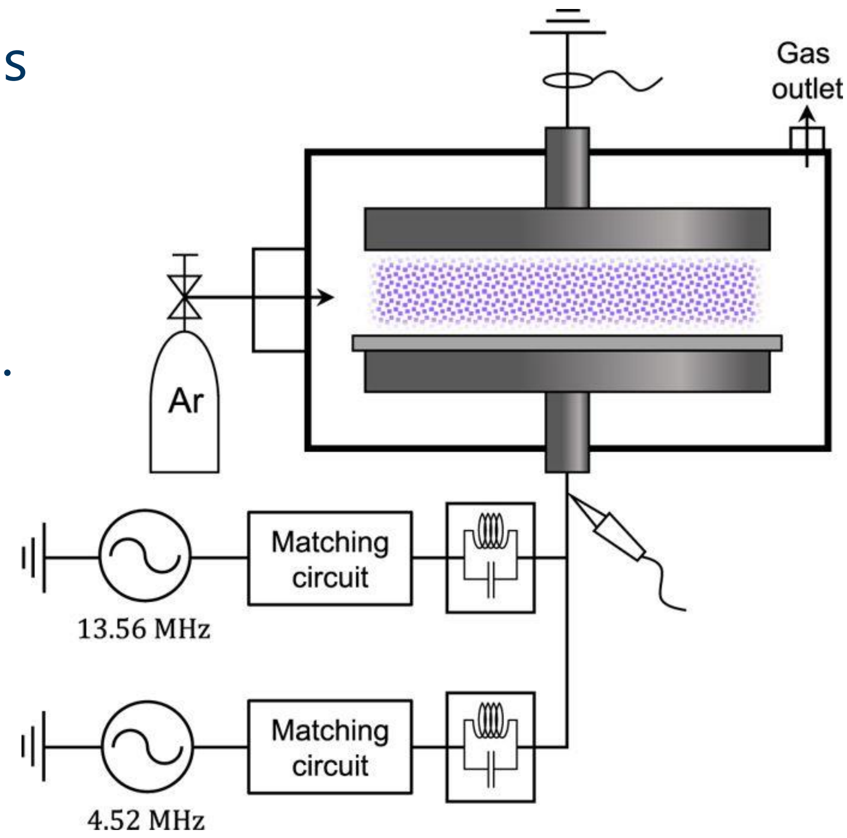
Particle and Potential distribution

$$\frac{V_p}{V_g} = \left(\frac{A_g}{A_p}\right)^4$$



Electrically Asymmetric

- The high frequency controls the ion plasma bulk (ion flux).
- The lower frequency controls the plasma sheath.
- The phase shift between the two sources controls also the sheath potential.
- The independent control is not always perfect.



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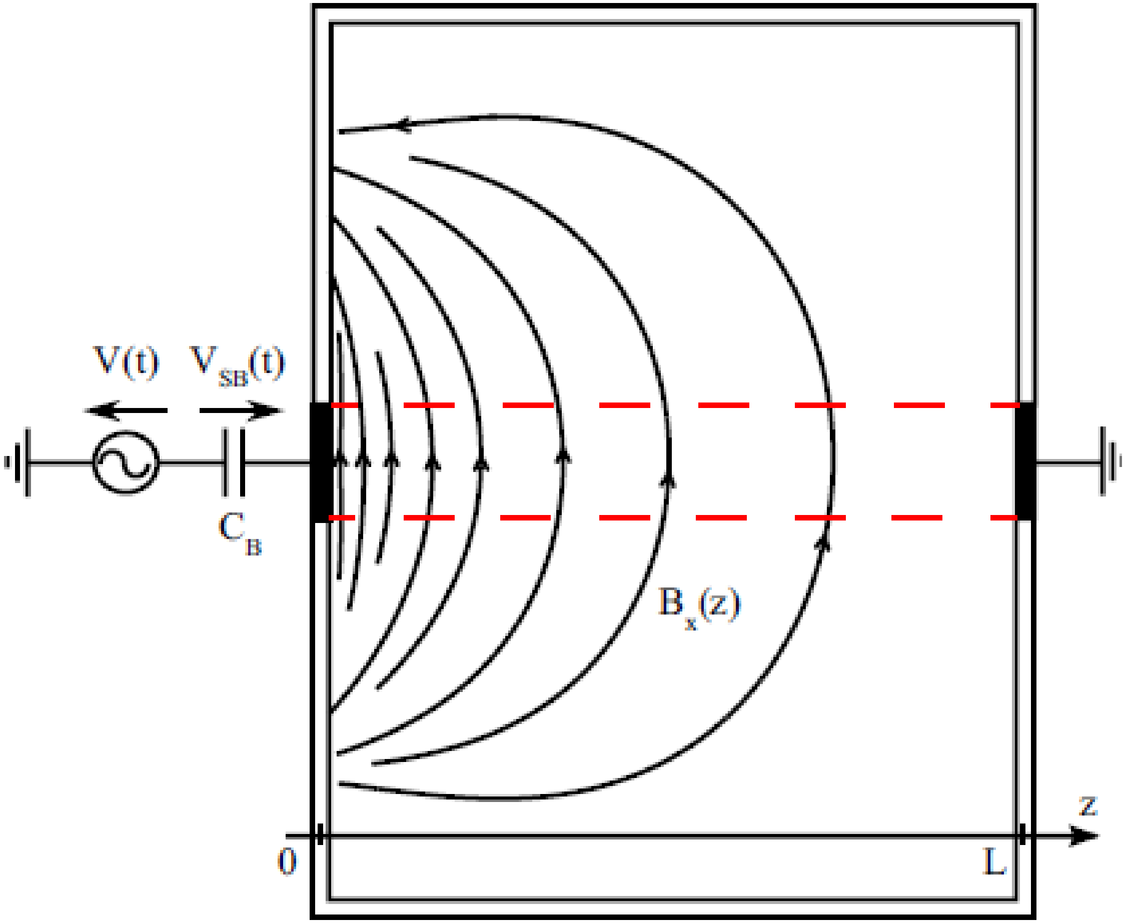
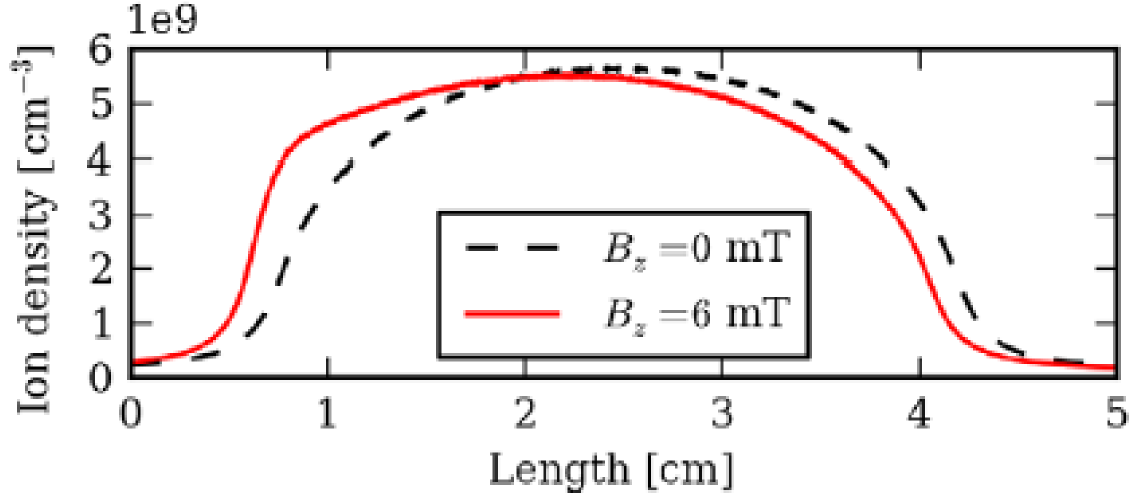
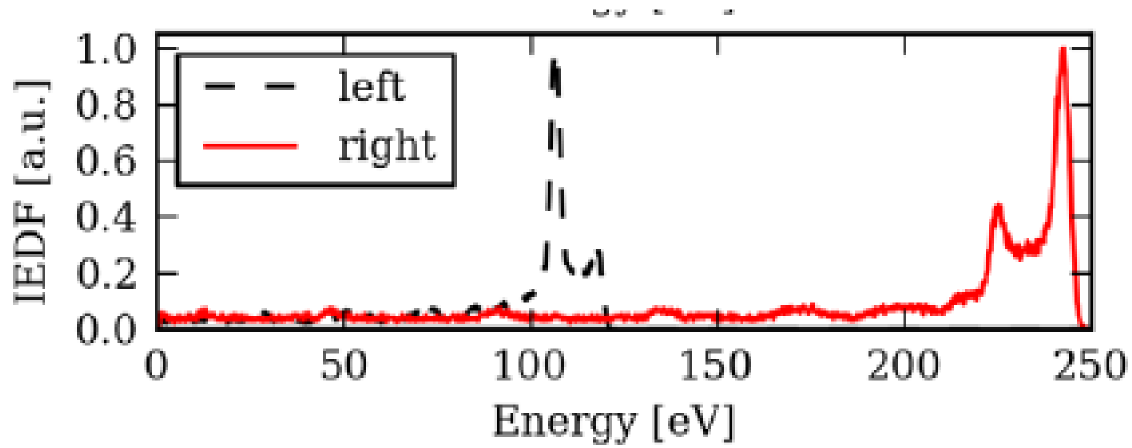
Magnetron

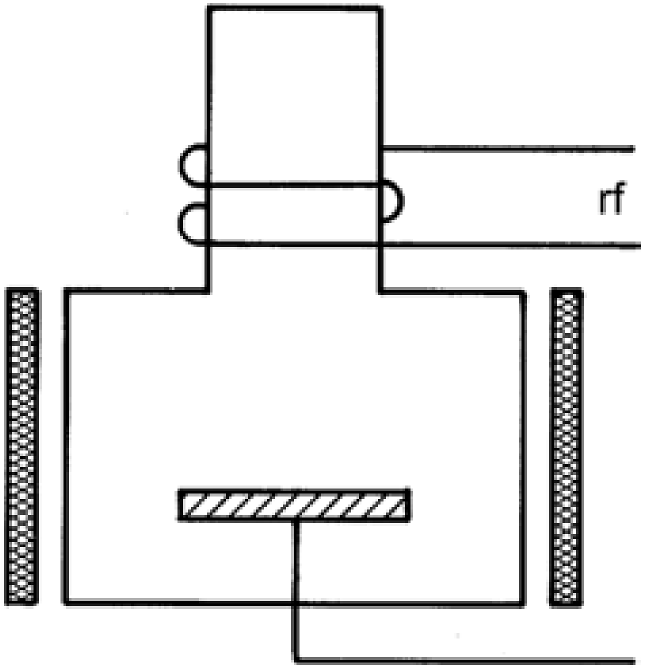


Magnetic Asymmetry

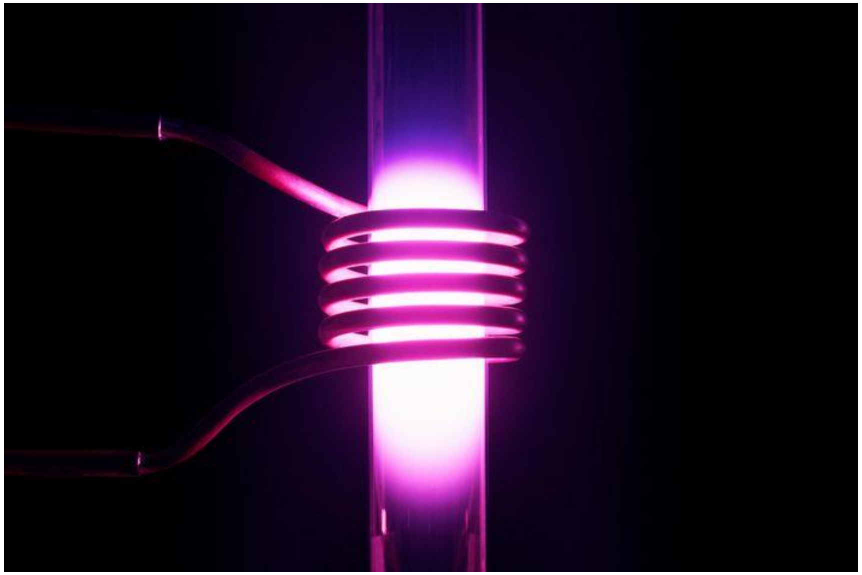




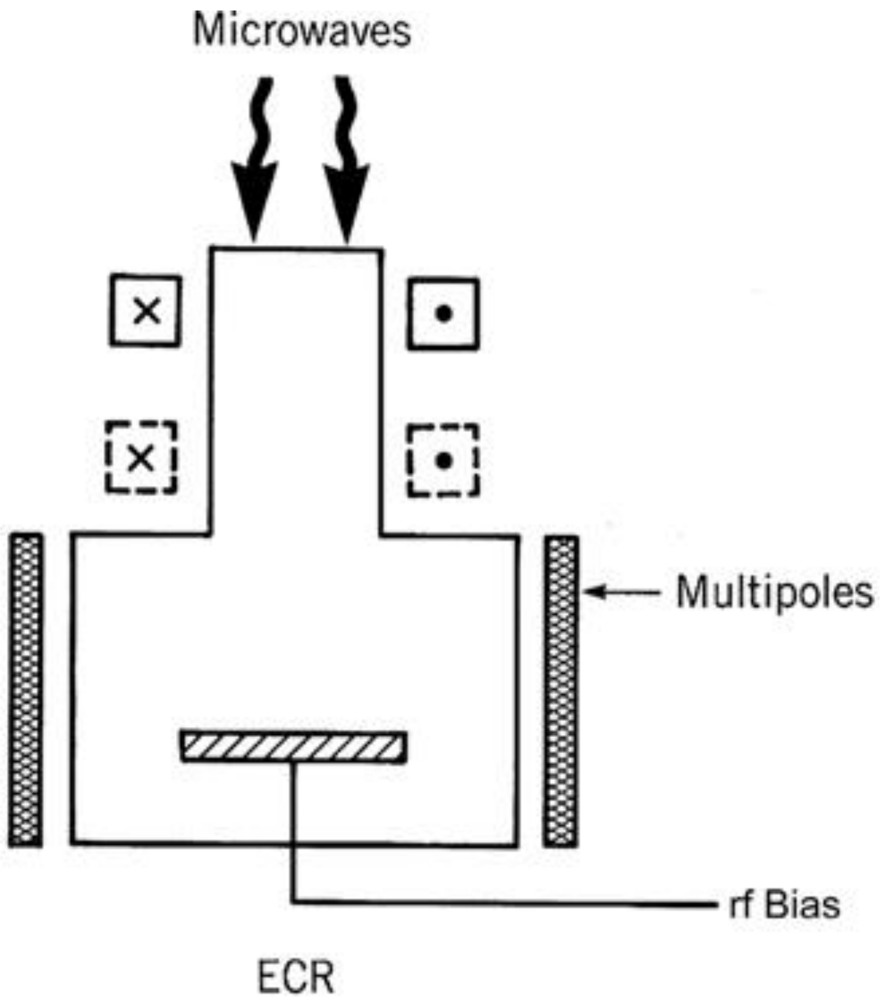
High density sources (ICP)



Inductive



High density sources (ECR)



Typical CCP parameters

$$V_{\mathrm{E}} = 250V$$

$$P_{\mathrm{g}} = 10\mathrm{mTorr}$$

$$\Gamma_{\mathrm{i}} = 1A/m^2$$

$$T_{\mathrm{e}} = 4eV$$

$$\omega_{\mathrm{rf}} = 2\mathrm{MHz}$$

What are optimum plasma etching parameters?

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The anistropy of the etching profile

- The etching profile is mainly determined by the ion flux, the ion energy, and the ion angular distribution.

- High aspect ratio could be achieved employing narrower ion angular distribution.

- Assuming an etching profile as a hole, the aspect ratio is the ratio of the height of the hole to the diameter of the hole;

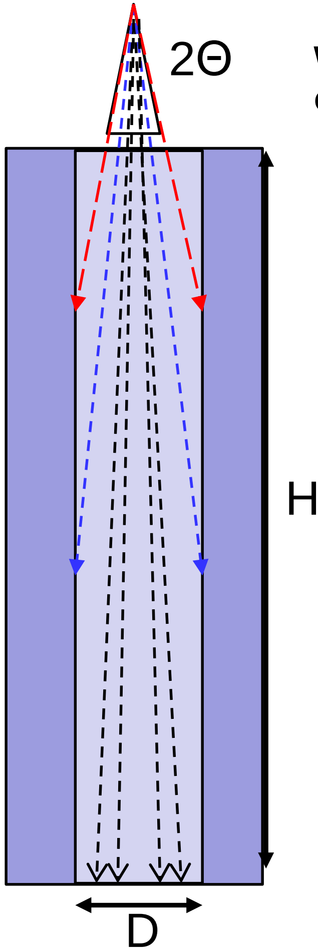
  AR=H/D.

- The direct ion heat flux hits the bottom of the contact is given by

$$\text{Direct ion flux} = \frac{\Gamma_i}{\Delta\theta}\int_{\theta-\Delta\theta/2}^{\theta+\Delta\theta/2} IAD(\theta')d\theta'$$

- The direct ion heat flux which a combination of the angular distribution and the ion energy distribution is given as

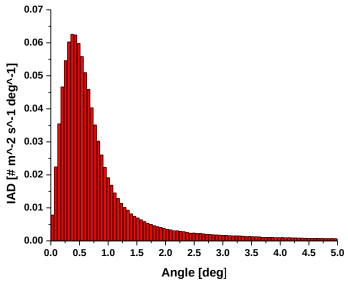
$$\text{Direct ion heat flux} = \frac{\Gamma_i}{\Delta\theta}\int_{\theta-\Delta\theta/2}^{\theta+\Delta\theta/2}\int_{\varepsilon_{min}}^{\varepsilon_{max}} IAED(\theta',\varepsilon)\ d\varepsilon\ d\theta'$$



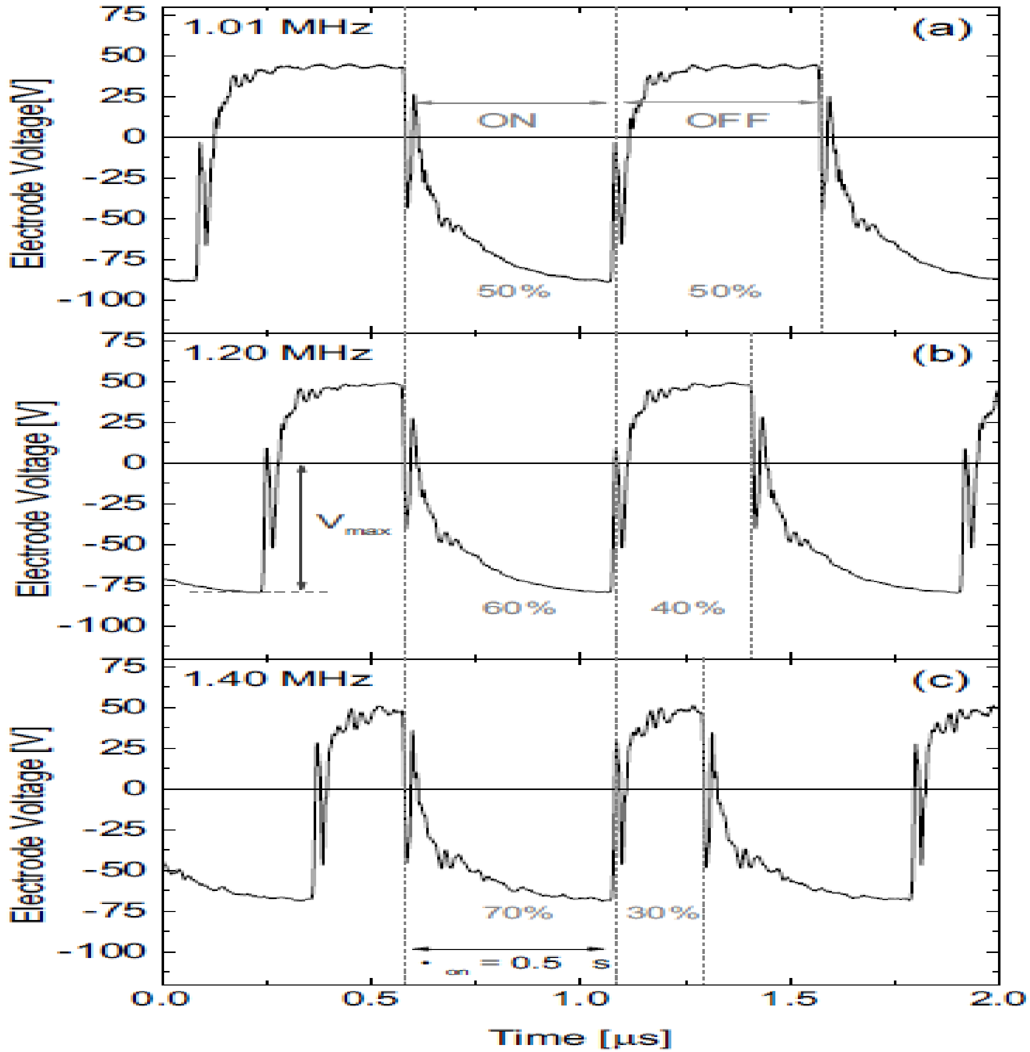
Contact Hole

where 2Θ is the angle of view : $\tan(\Theta)=D/2H$

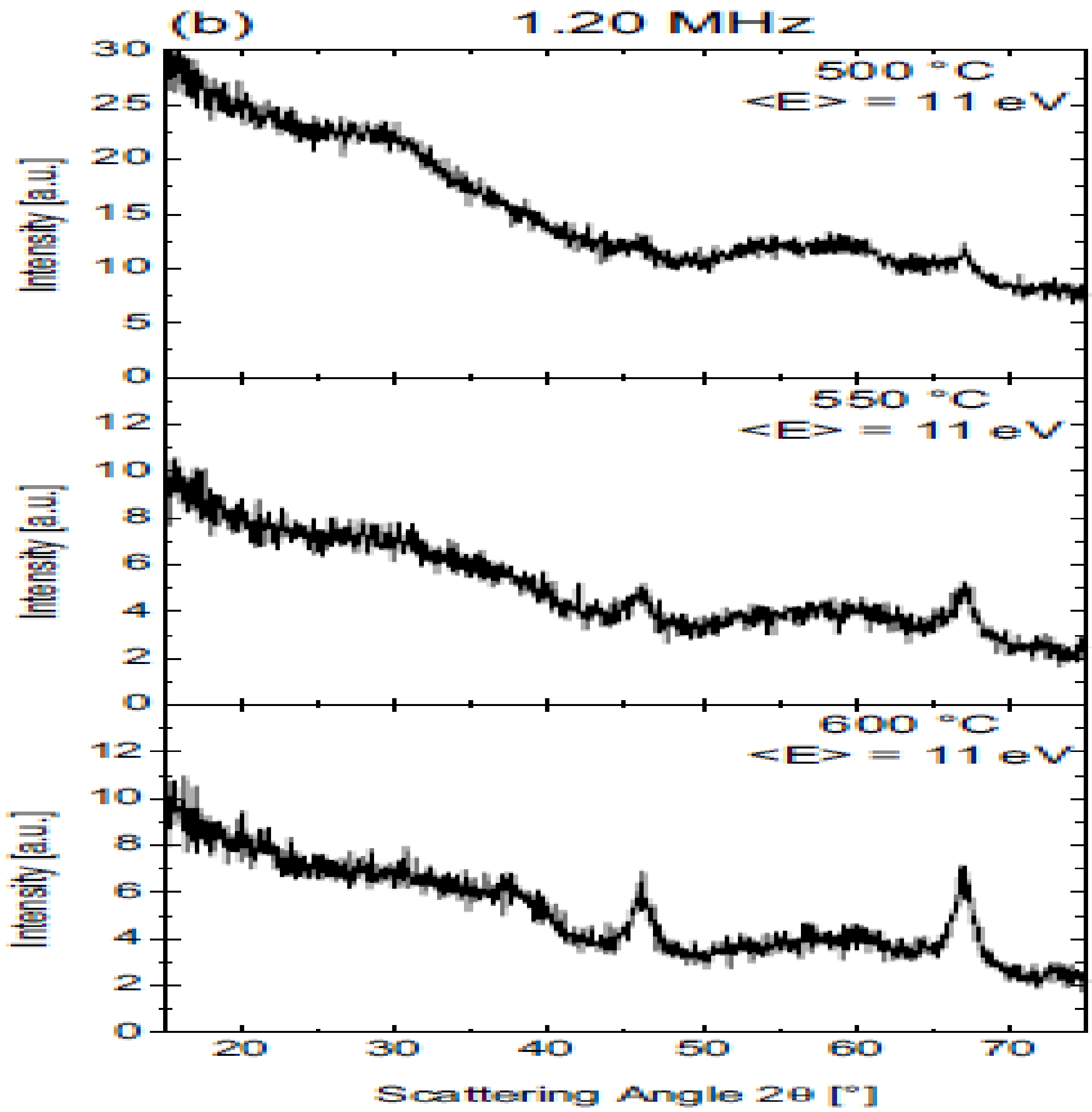
$$5\text{nm} \times 100\text{nm}$$



Aluminum Oxide Deposition I

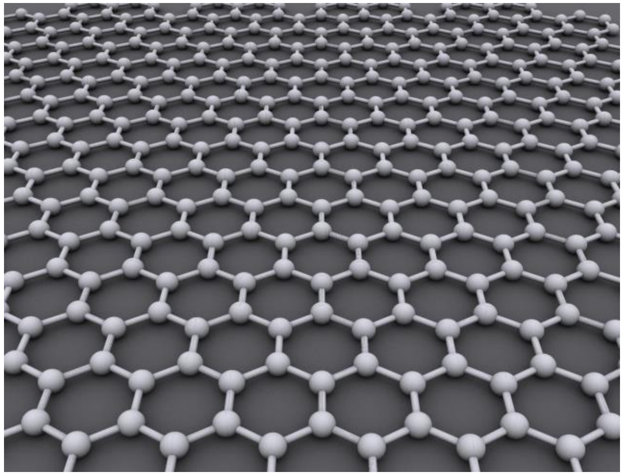


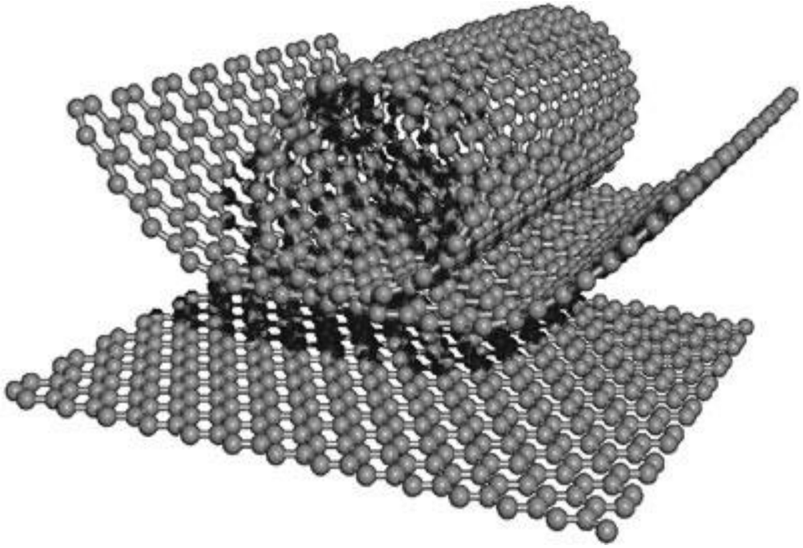
Aluminum Oxide Deposition II



Graphene

- It is a single layer of Carbon atoms arranged i a hexagonal lattice





- Zero band gap material
- The strongest material: 200 times steel
- Conducts heat and electricity effeciently
- Transparent
- Nonlinear diamagnetism

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Graphene applications

Unbreakable smart phones

Computer chip faster 10000 than normal chip

Batteries and super capacitors
Storage more energy
Charge faster

Low cost solar cells

Bone Tissue engineering

Drug delivery
Remove radioactive materials from water

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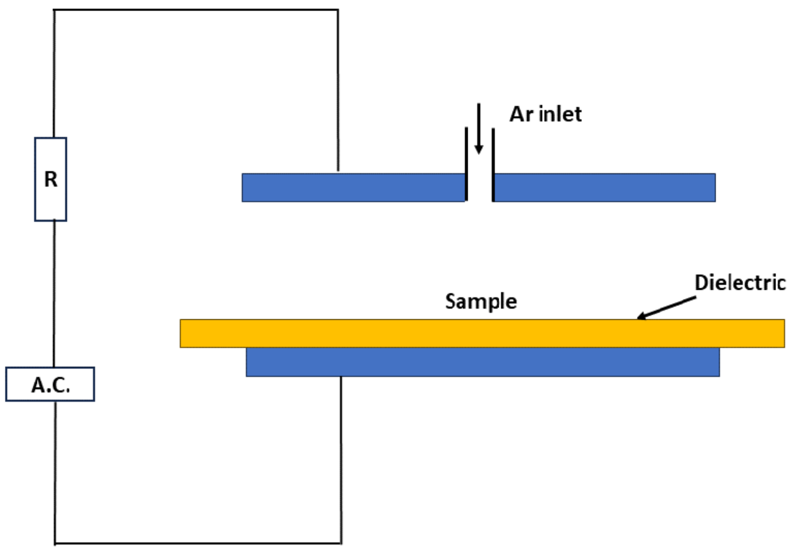
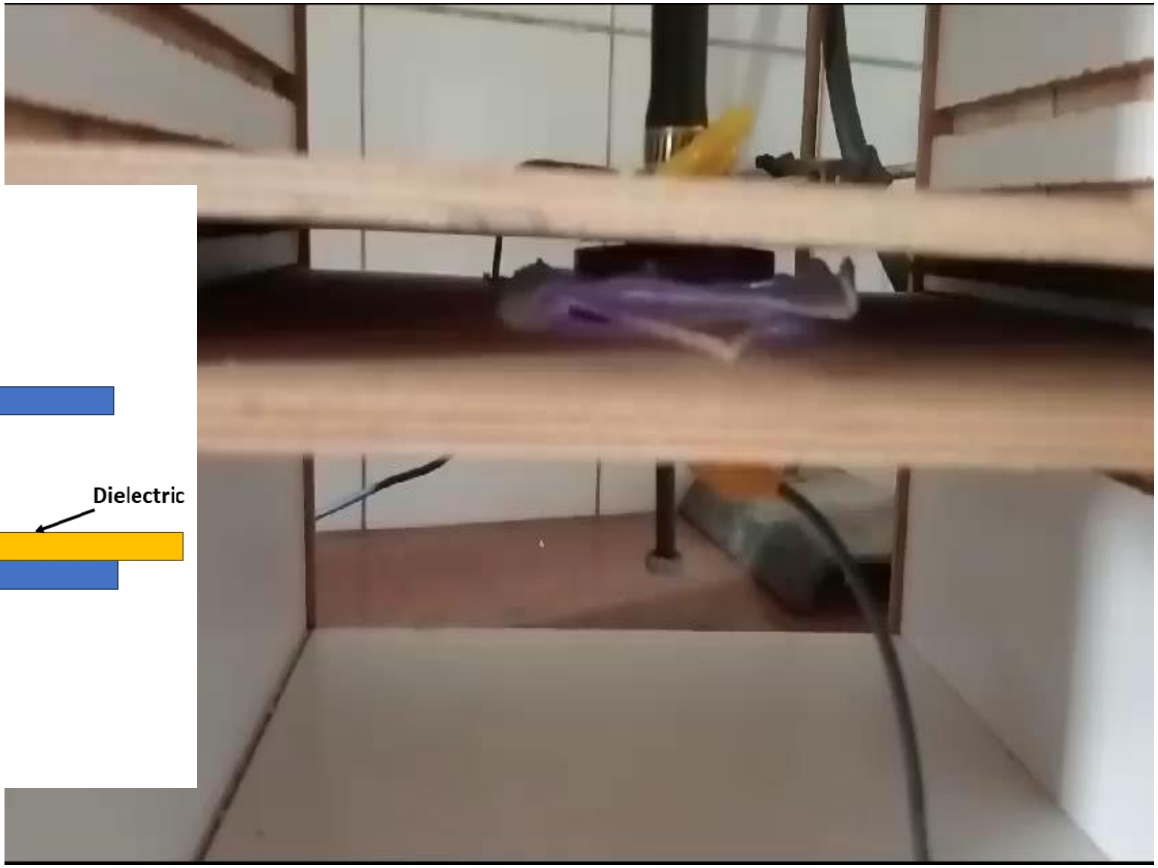
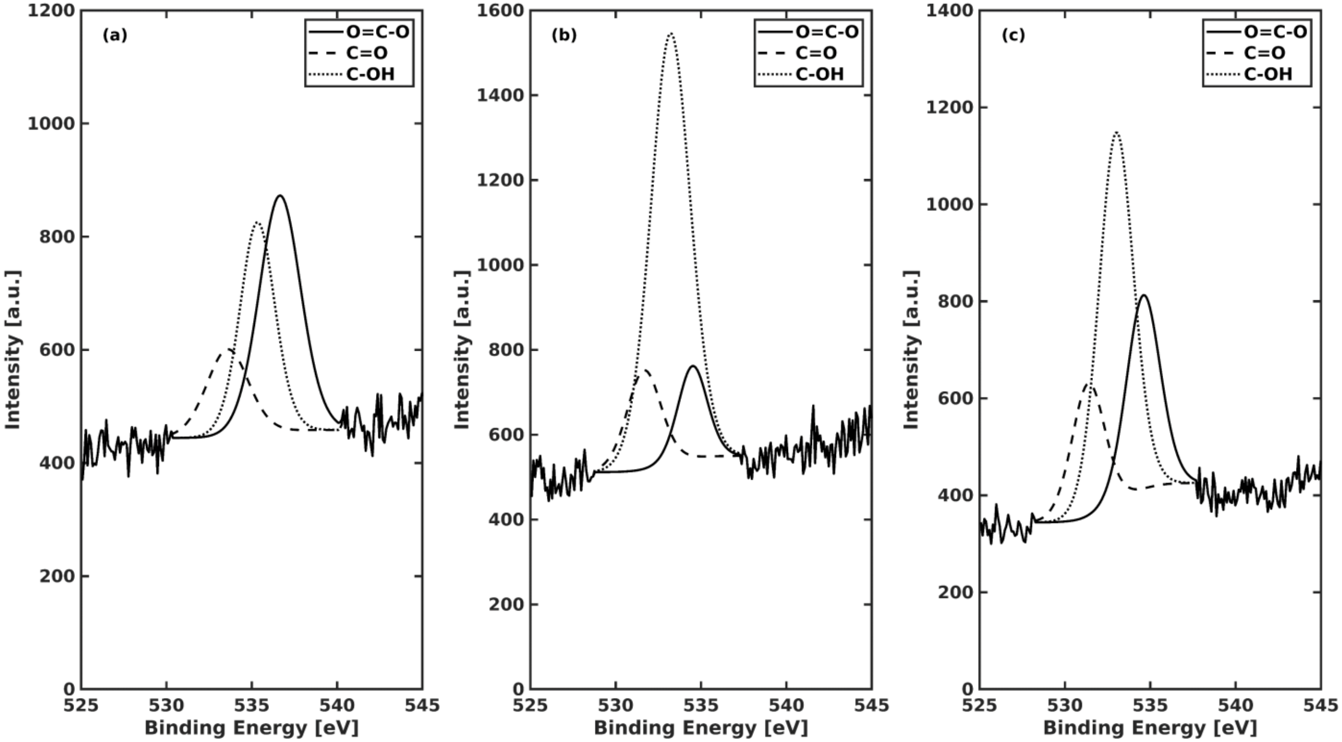
Devices in our Lab





Devices in our Lab

X-ray photoelectron spectroscopy (XPS)



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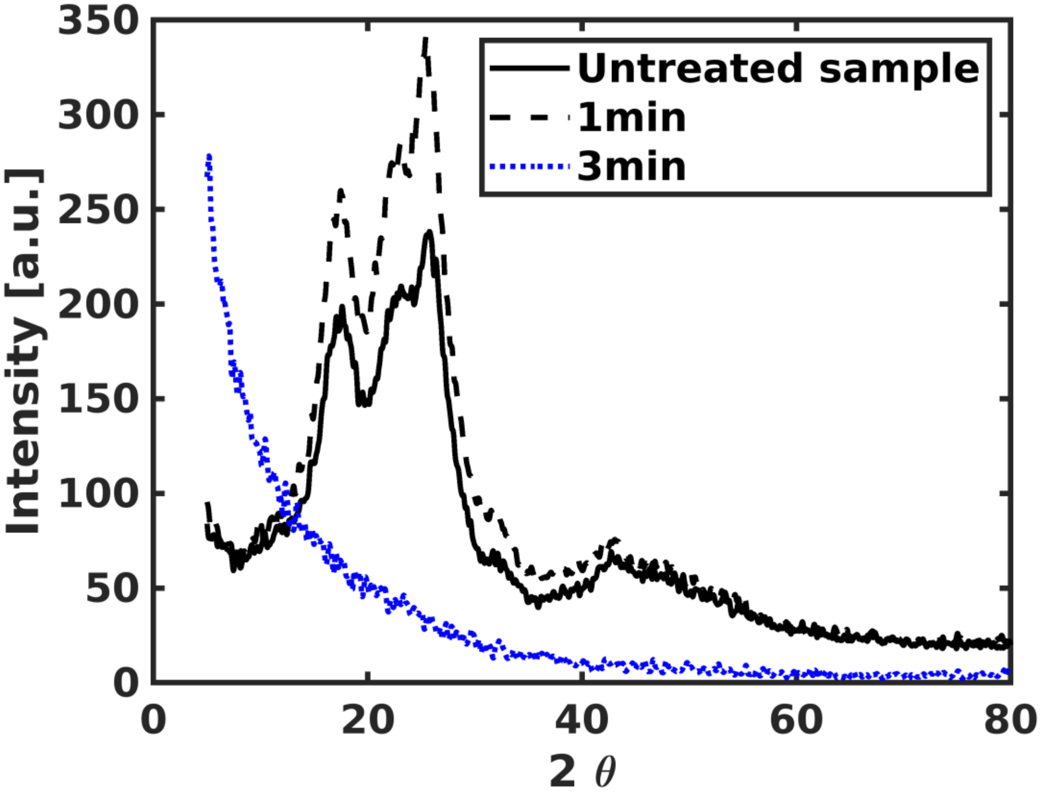
X-ray diffraction



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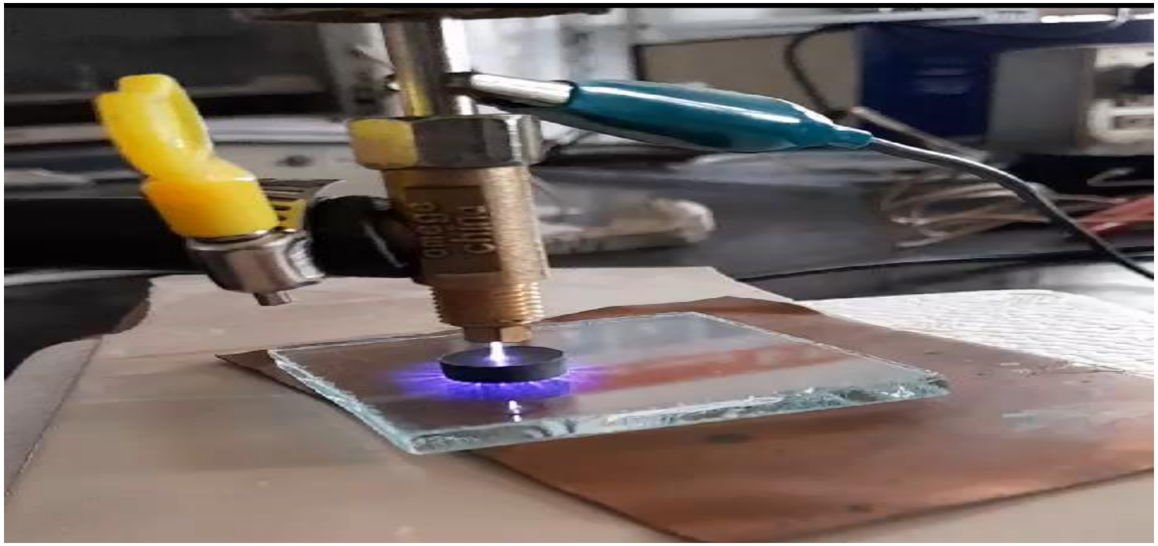
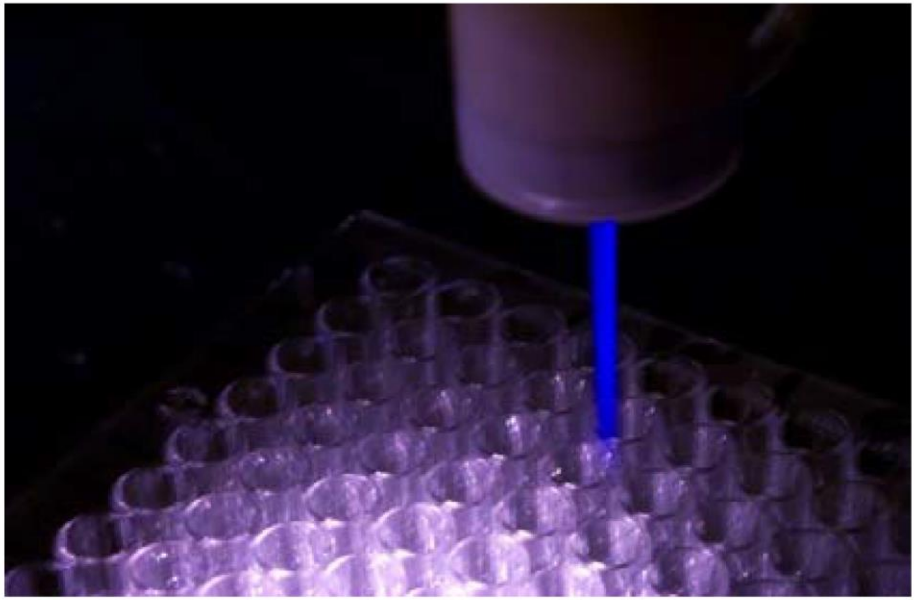
Devices

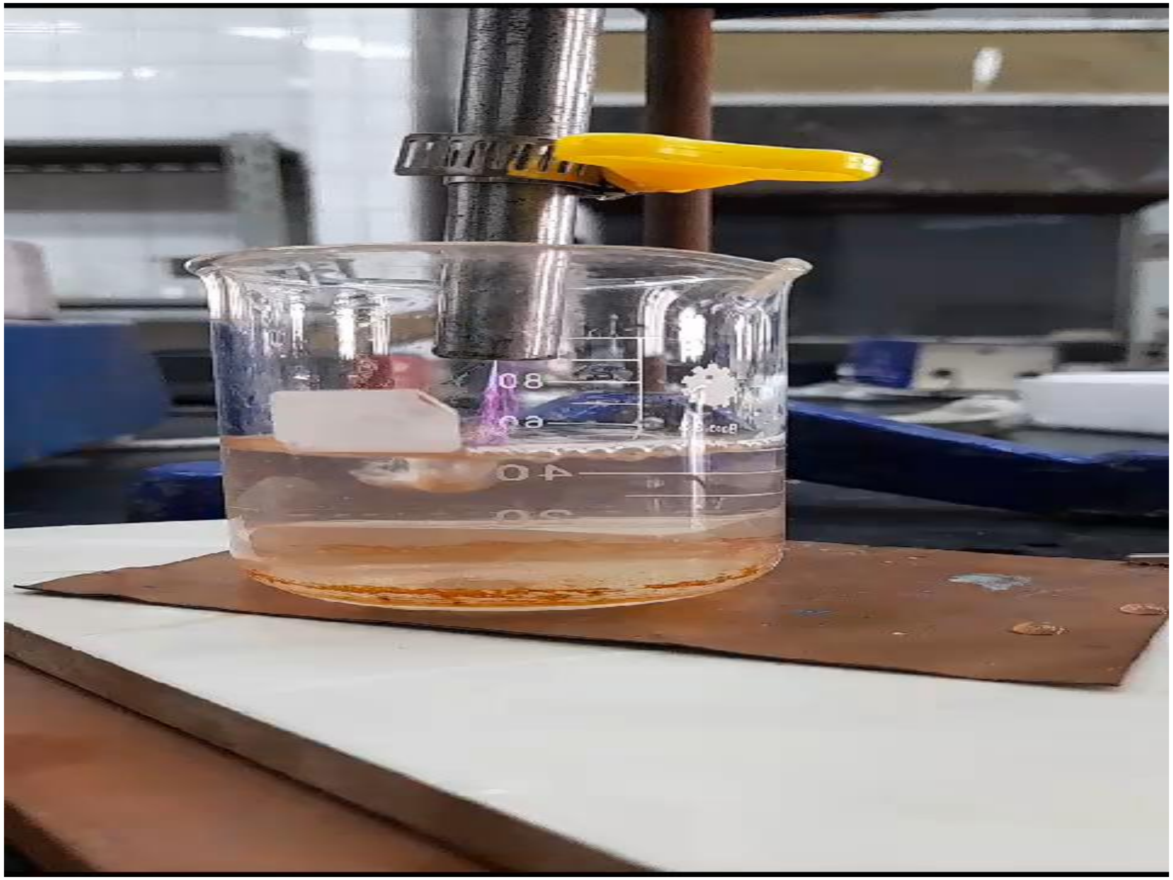




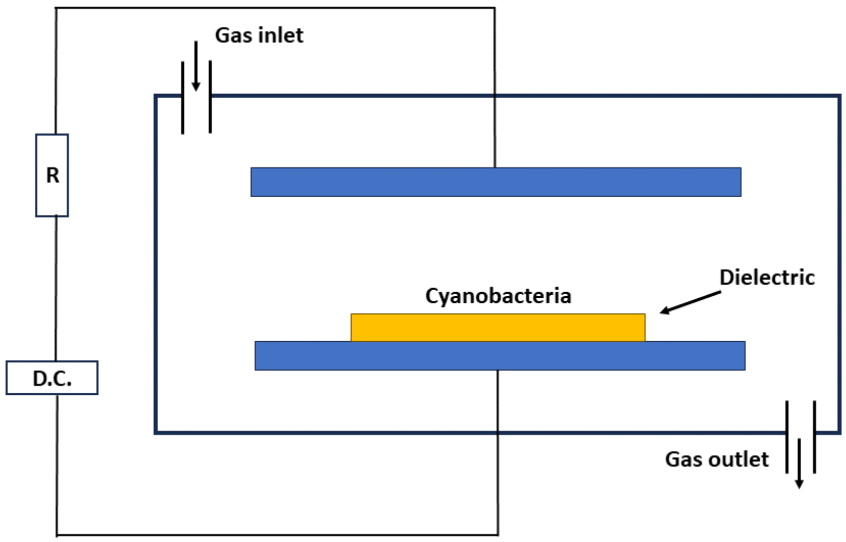
(a)

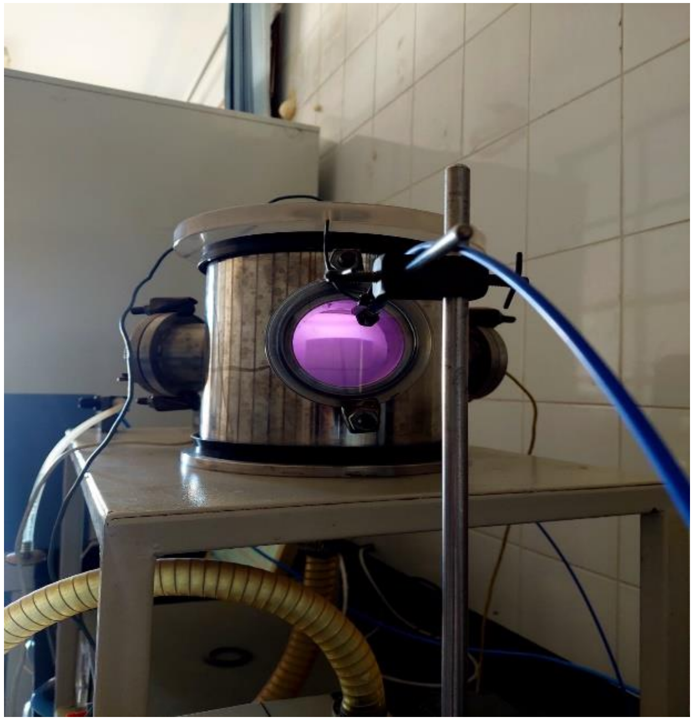
(b)

Devices



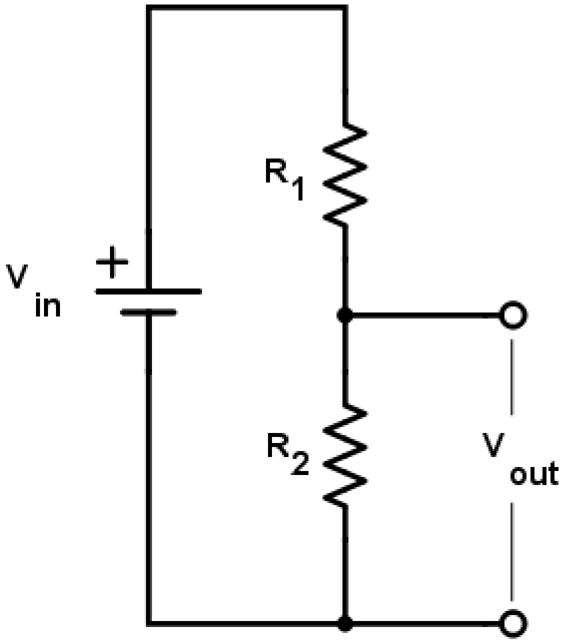
Devices in our Lab





High Voltage Probe

High Voltage Probe



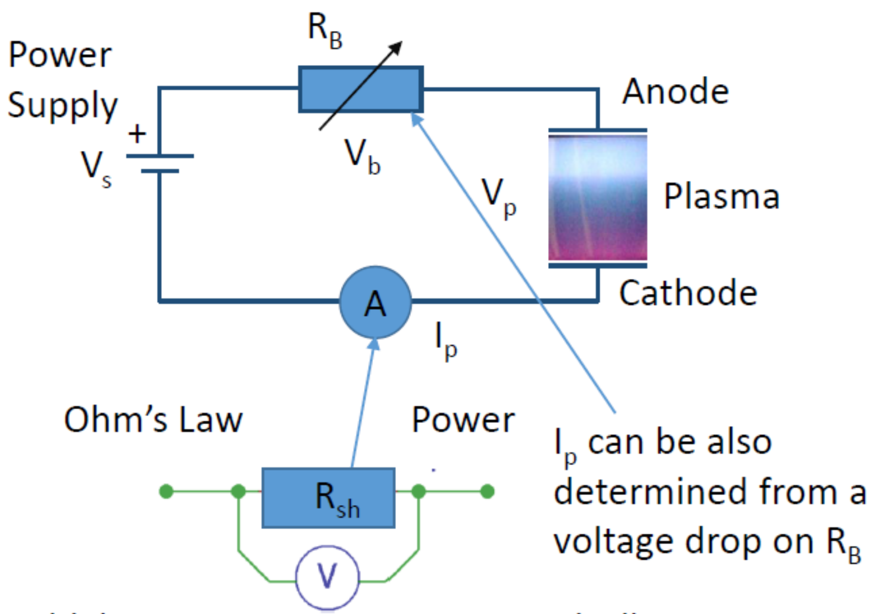
$$V_{in} = I(R_1 + R_2)$$

$$V_{out} = IR_2$$

$$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_1 + R_2}$$

When $R_2 \ll R_1$ Then $V_{out} \ll V_{in}$

DC Current Measurements



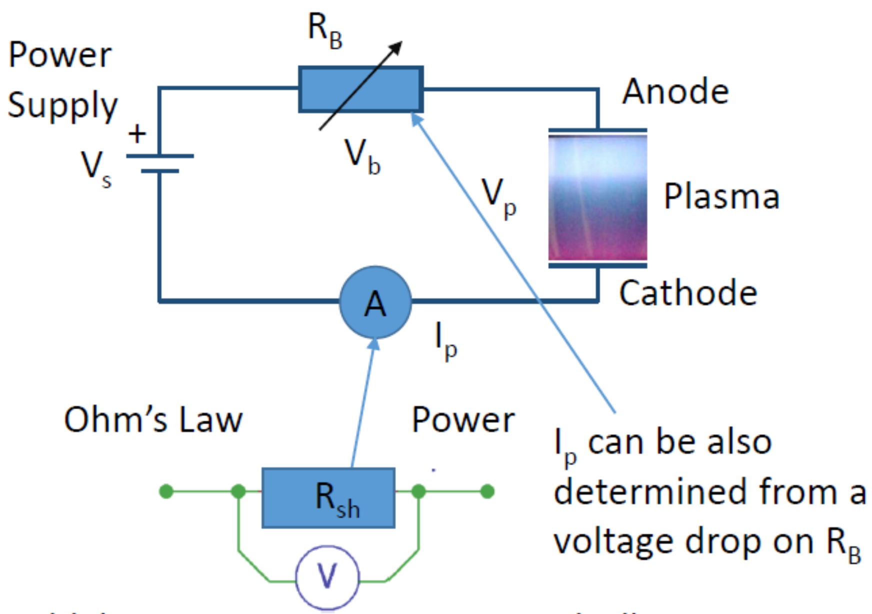
Typical accuracy ~1%
Range V: mV to kV
Range A: mA to A

34465A

Typical accuracy ~0.01%
Range V: mV to kV
Range A: microA to A

Shunt resistor for DC: V=IR

AC Current



Typical accuracy ~1%
Range V: mV to kV
Range A: mA to A

34465A

Typical accuracy ~0.01%
Range V: mV to kV
Range A: microA to A

For AC, replace the resistance with capacitor

$$V = Q/C \qquad I = C\frac{dV}{dt}$$

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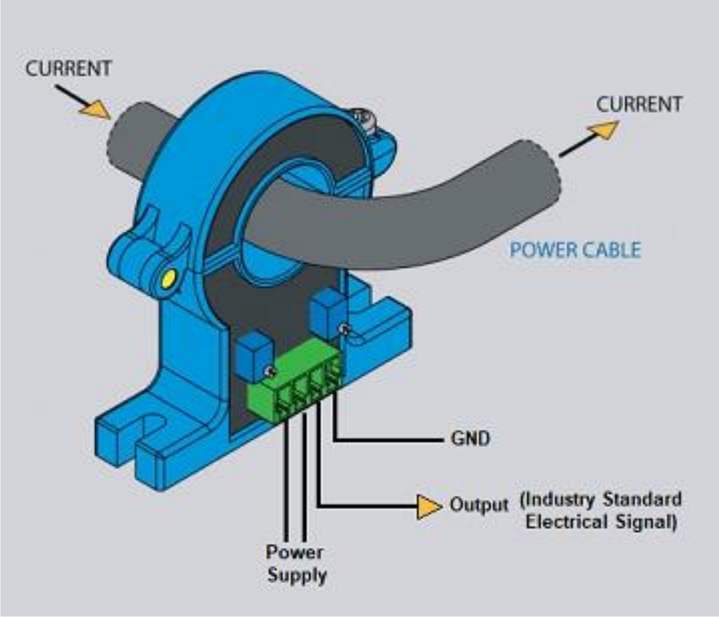
Current Sensors

A current sensor is a dvice that detects and converts current to an easily measure output voltage

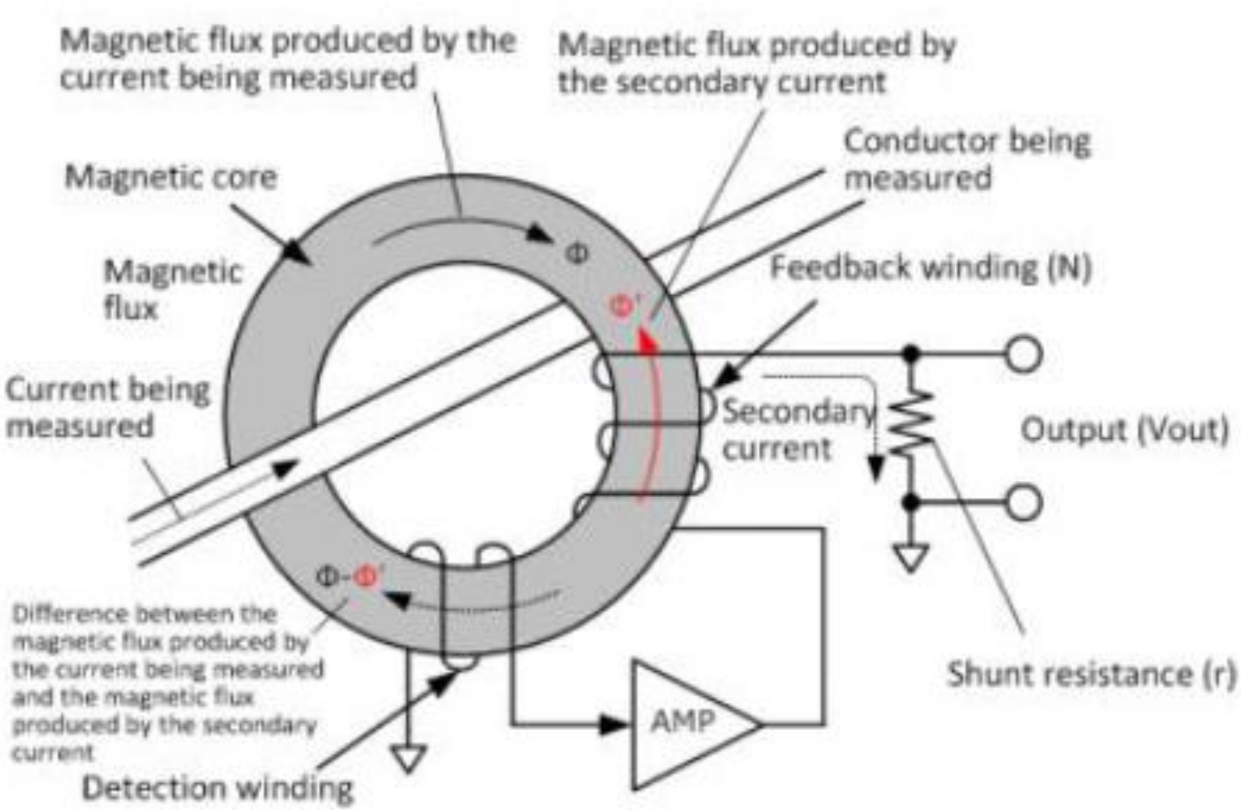
Current transducer



Current Sensors

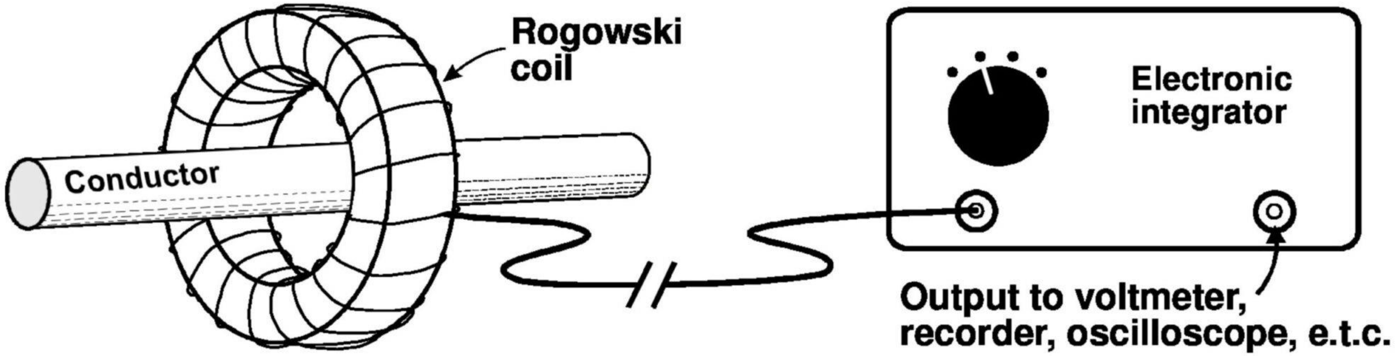
A current sensor is a dvice that detects and converts current to an easily measure output voltage

Zero-flux type (AC)



Current Sensors

A current sensor is a dvice that detects and converts current to an easily measure output voltage



A Rogowski coil is an 'air-cored' toroidal coil placed round the conductor. The alternating magnetic field produced by the current induces a voltage in the coil which is proportional to the rate of change of current.

$$V = M\frac{dI}{dt}$$

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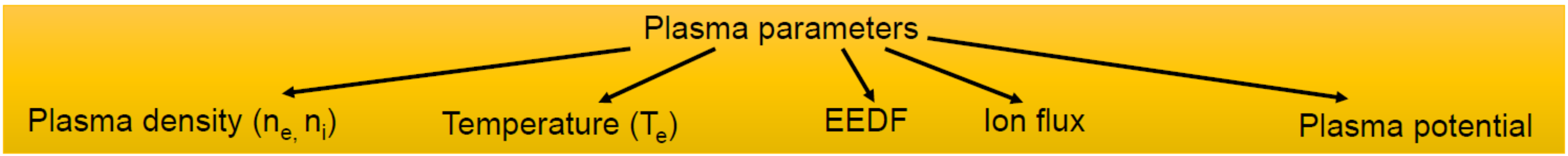
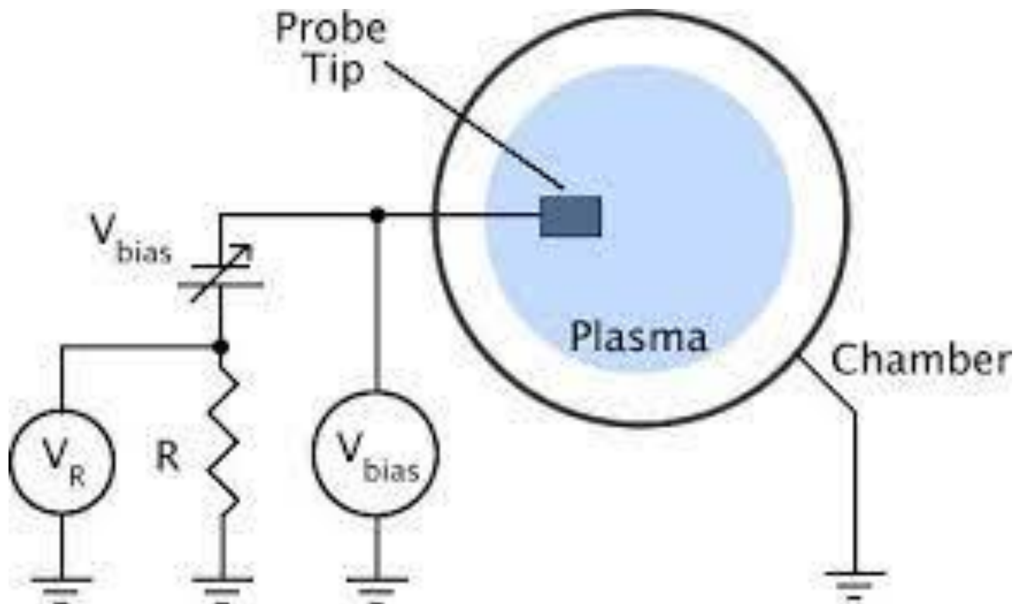
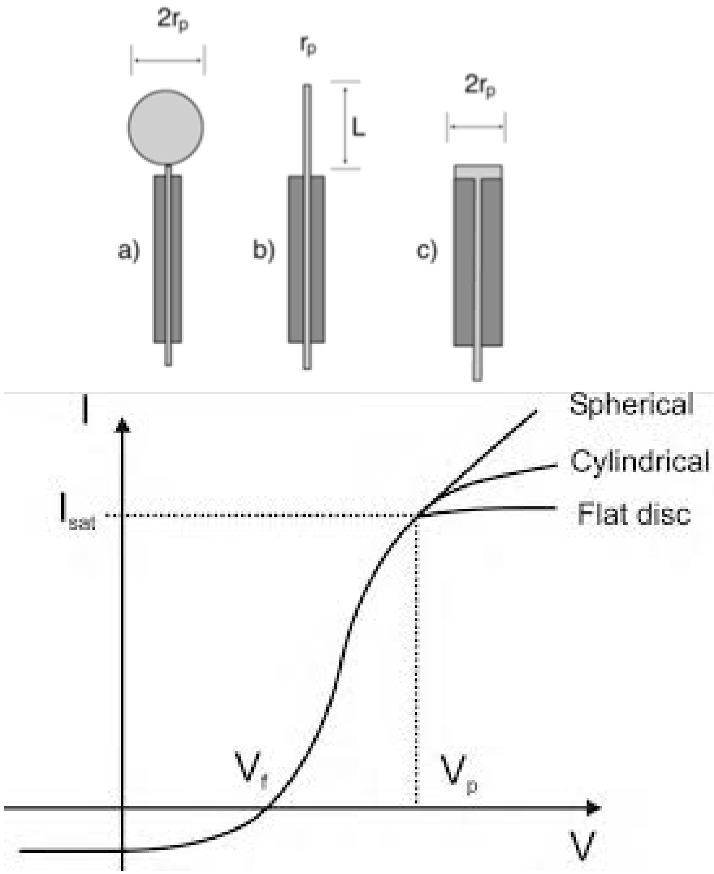
Langmuir Probe

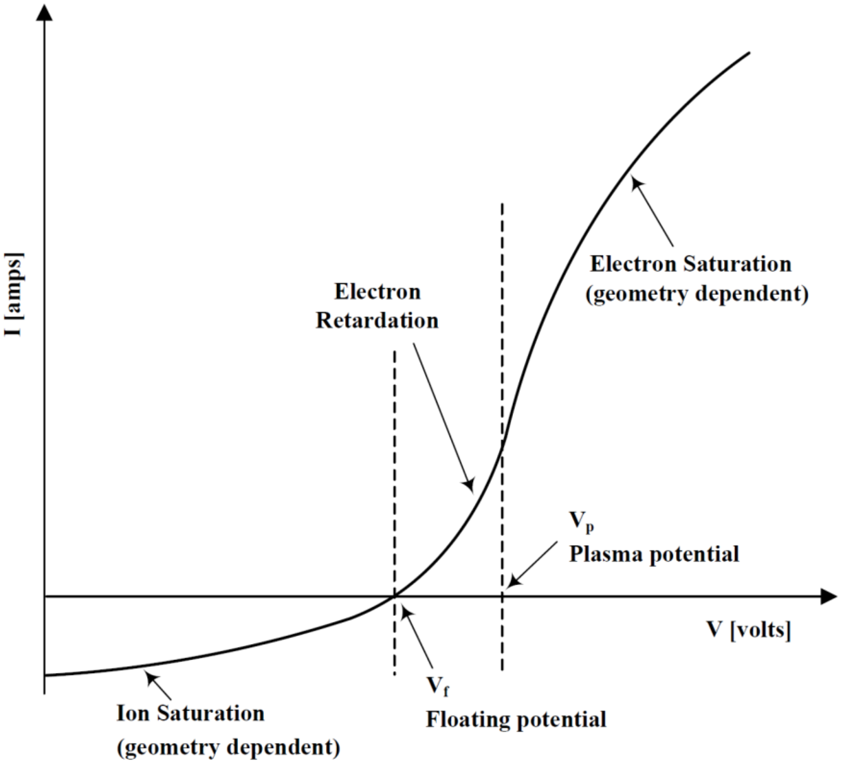
One of the most frequently employed methods for plasma diagnostics is Langmuir probes.





Langmuir Probe

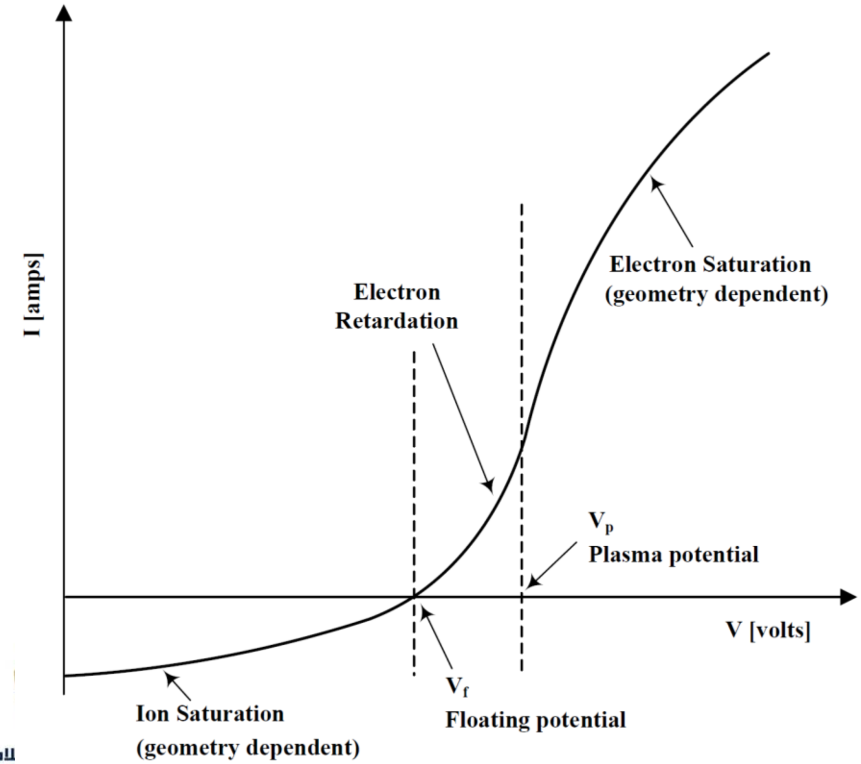




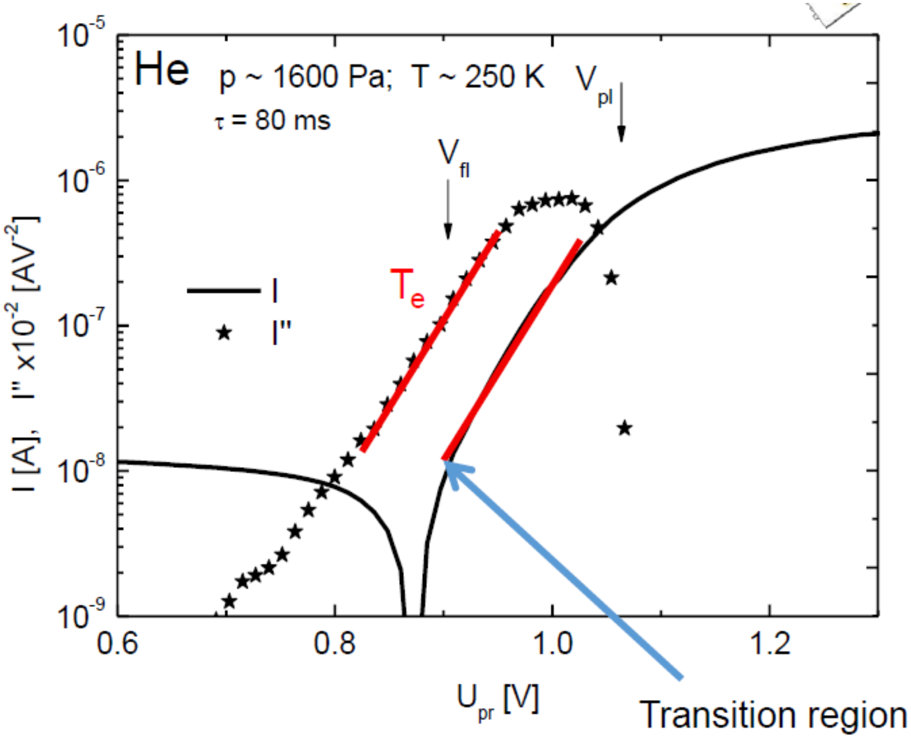
Langmuir Probe

The electron temperature T_e for any plasma is well defined if the EEDF is Maxwellian

$$I_e(V) = I_{e0} \exp\left(-\frac{eV}{kT_e}\right)$$



$$\ln[I_e(V)] = \ln[I_{e0}] - \frac{e}{kT_e}V$$



Challenges of plasma simulation

- The most accurate method is to solve the equation of motion of each particle in the plasma.

$$m\frac{d\vec{v}_k}{dt} = e\vec{E}_k + e\vec{v}_k \times \vec{B}_k$$

- No. of particles is very very large $n = 10^9 - 10^{13}\mathrm{cm}^{-3}$
- Maxwell equations

$$\vec{\nabla} \cdot \vec{D} = \rho_v \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{H} = \vec{J} + \epsilon\frac{\partial \vec{E}}{\partial t}$$

- The collective behaviour and the huge number of particles make the solution impossible in such way.

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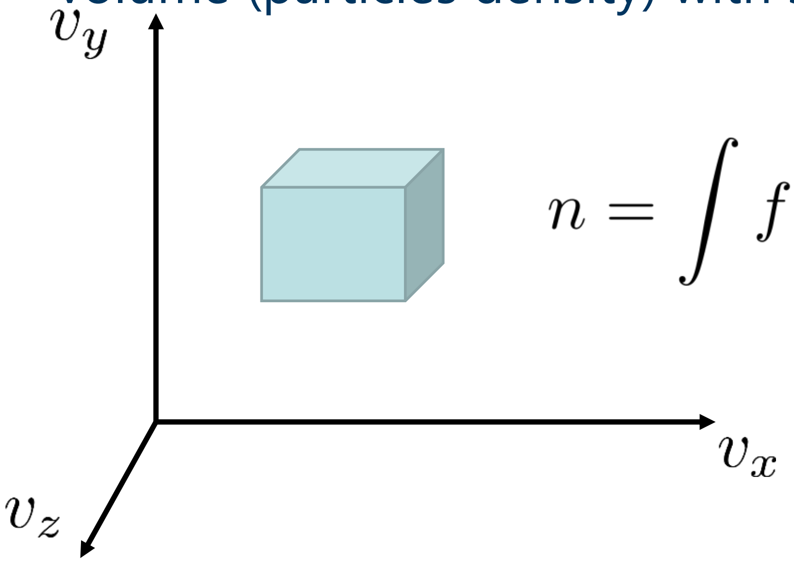
The distribution function

- The distribution function gives the number of particles per unit volume (particles density) with speed v as a function of time.



$$n = \int f(r, v, t) d^3v$$

- The kinetic equation is an integro- deffrential equations in 7 parameters

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_r f + \vec{a} \cdot \vec{\nabla}_v f = \text{collision terms}$$

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Macroscopic description

- Instead of known the physical parameters of each particle, one can calculate the average values for the whole plasma system.

- Average plasma density

$$\bar{n} = \int f(r,v,t)d^3v$$

- Average speed

$$\bar{v} = \int vf(r,v,t)d^3v/\bar{n}$$

- Kinetic energy

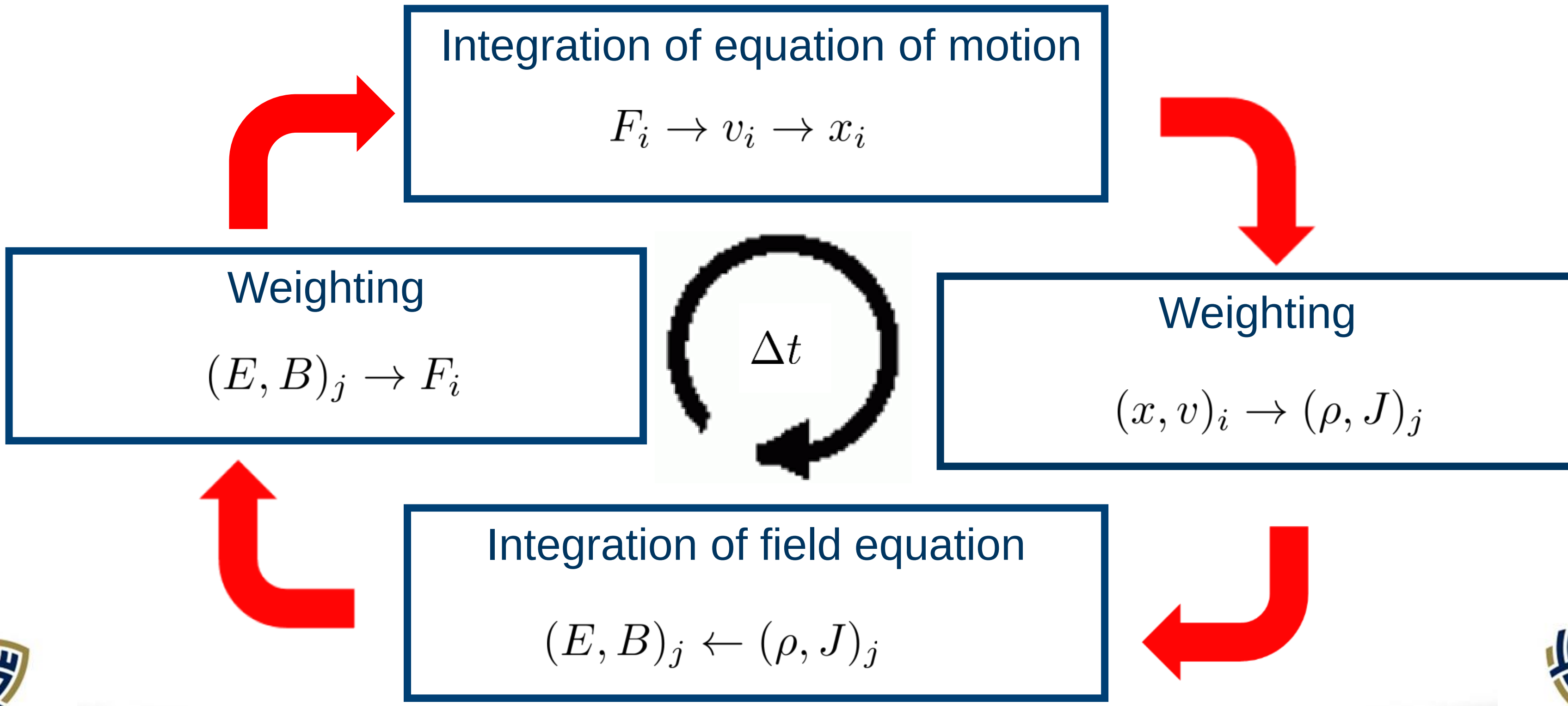
$$\bar{E}_k = \int \frac{1}{2}mv^2 f(r,v,t)d^3v/\bar{n}$$

- Avergaes over Boltzman equation

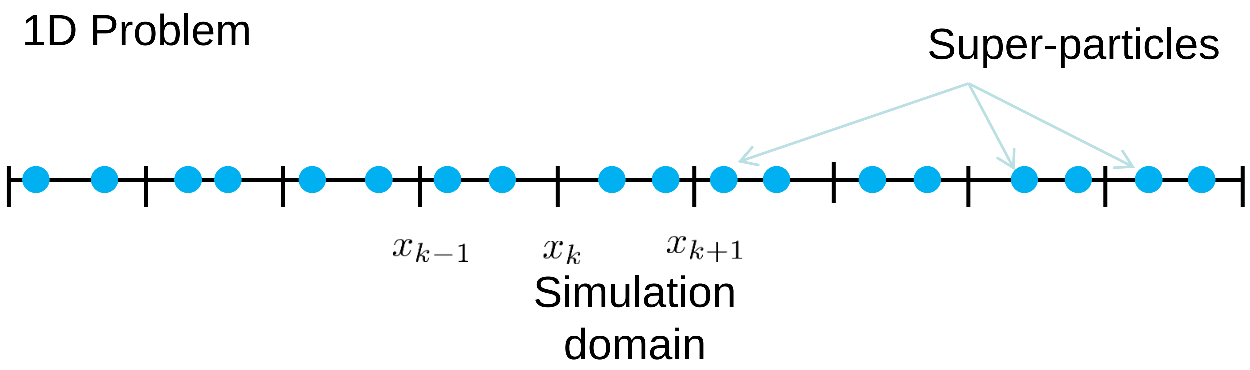
$$mv^q(\frac{\partial f}{\partial t} + \vec{v}\cdot\vec{\nabla}_r f + \vec{a}\cdot\vec{\nabla}_v f) = \text{collision terms}$$
$$q = 0, 1, 2, 3, \ldots$$

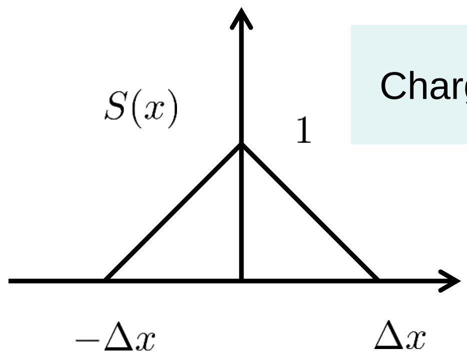
Kinetic Description

- Kinetic means „of or relating to motion“.
  - It is impractical to solve the equation of motion of all plasma particles.
  - Boltzman equation is an integro-differential equation.
- Particle-in-Cell : Super particle $10^6 - 10^9$ real particles.



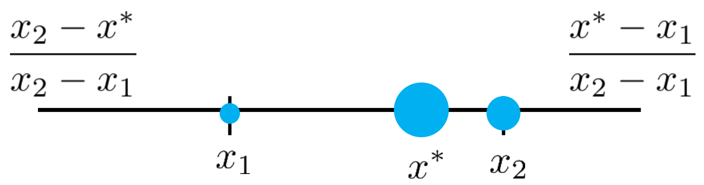
Particles





Charge cloud

First order wieghting



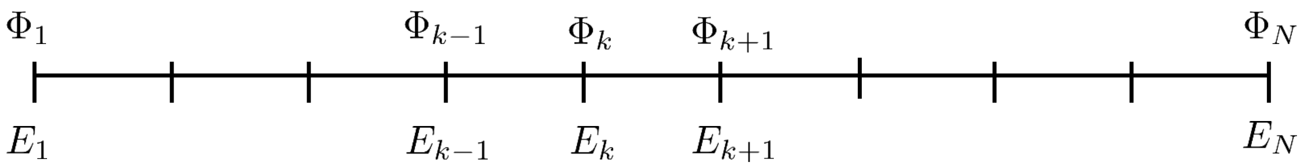
Fields

Poisson's eq.

$$\nabla^2 \Phi = -\frac{\rho}{\epsilon} \quad \longrightarrow \quad \frac{\Phi_{k+1} - 2\Phi_k + \Phi_{k-1}}{\Delta x^2} = -\frac{\rho}{\epsilon}$$

Boundary condition

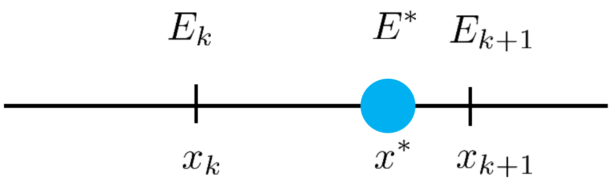
Boundary condition



$$E_1 = -\frac{\Phi_2 - \Phi_1}{\Delta x} - \rho_1 \frac{\Delta x}{2\epsilon} \qquad E_k = -\frac{\Phi_{k+1} - \Phi_{k-1}}{2\Delta x} \qquad E_N = -\frac{\Phi_N - \Phi_{N-1}}{\Delta x} + \rho_N \frac{\Delta x}{2\epsilon}$$

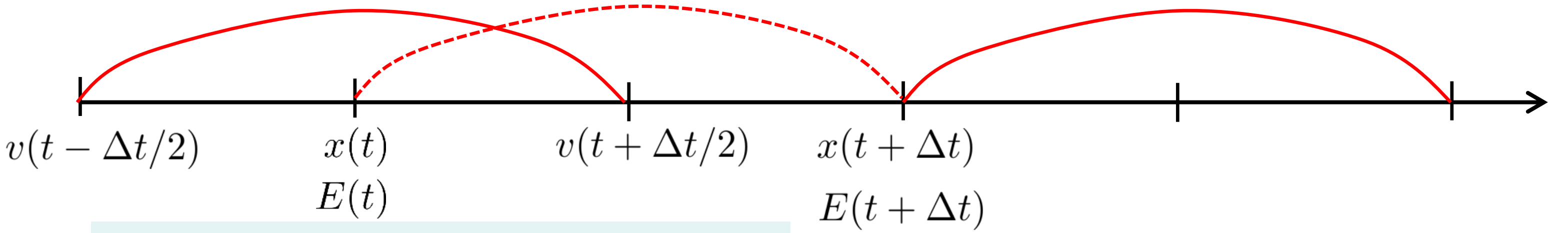
Interpolation of the fields to the particle positions

$$E^* = \frac{x^* - x_k}{\Delta x} E_{k+1} + \frac{x_{k+1} - x^*}{\Delta x} E_k$$



Pushing particles

„Leapfrog“ scheme



Descritization of equation of motions

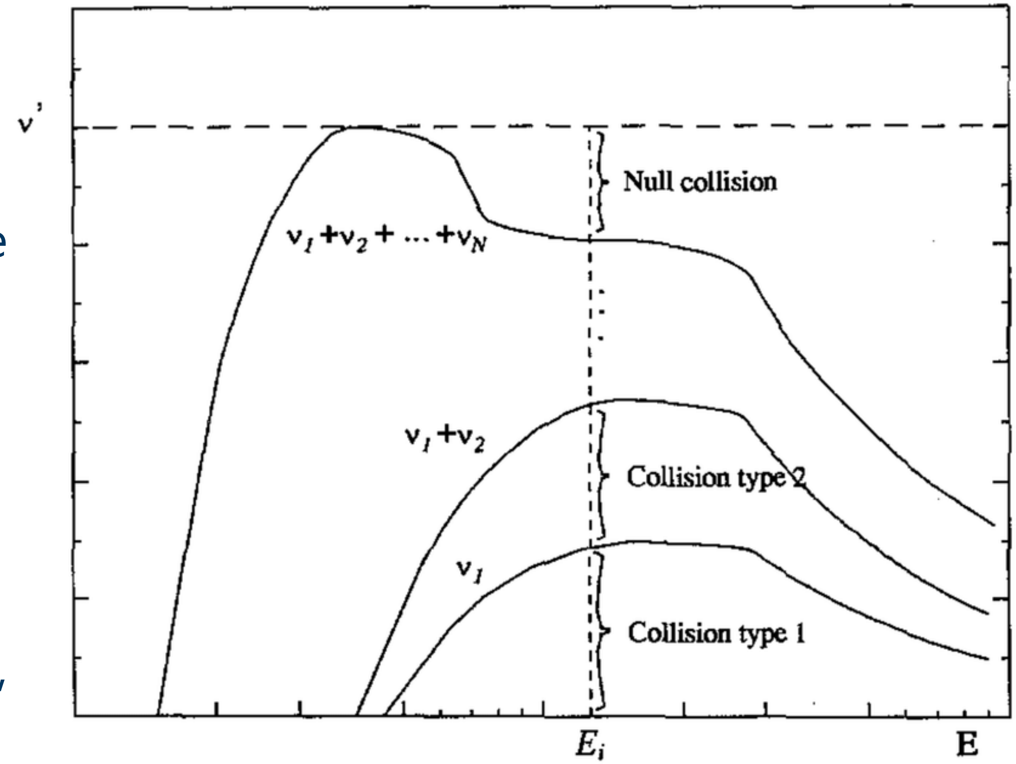
$$\frac{v(t+\Delta t/2)-v(t-\Delta t/2)}{\Delta t}=\frac{q}{m}E(t)$$

$$\frac{x(t+\Delta t)-x(t)}{\Delta t}=v(t+\Delta t/2)$$

Monte-Carlo Scheme is required for collisions

Monte Carlo: null collision method

- Many collisions take place:
  impact ionization, charge exchange
  hard-shere, …
- Let the probability of them
  P1,P2,P3,P4, …
- Claculate the total probabilities PT
- Calculate relative probabilities
  P1/PT,   P2/PT,   P3/PT,   P4/PT,



- Generate a random number between [0,1]
- if   P1/PT= < The randum number<(P1+P2)/PT
- Event 1 takes place
- If not
  (P1+ P2)/PT= < The randum number<(P1+P2+P3)/PT
- ……

Challenges of PIC simulation

- Numerical instabilities:
  - Accuracy criterion $\omega_p \Delta t \leq 0.2$
  - Courant criterion $v_{\max} \Delta t \leq \Delta x$
  - The computational grid has to resolve the Debye lenght $\Delta x \leq \lambda_D$

- In order to have a good statistics, a resonable high number of particles per Debye lenght must be used $N_D \gg 1$

- Keep the probabilty for collisions small

$$P_{\text{coll}} = 1 - e^{-\nu t} \leq 0.1$$

- Alternatives:
  - Implicit schems
  - Parrallilization

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Fluid Models

- Continuity, momentum, and energy equations are closed with Poisson's equation

$$\frac{\partial n_{\mathrm{e,i,m}}}{\partial t} + \vec{\nabla} \cdot \vec{\Gamma}_{\mathrm{e,i,m}} = G_{\mathrm{e,i,m}} - L_{\mathrm{e,i,m}},$$

$$\vec{\Gamma}_{\mathrm{e,i,m}} = \mathrm{sign}(q_{\mathrm{e,i,m}})\ n_{\mathrm{e,i,m}}\ \mu_{\mathrm{e,i,m}}\ \vec{E} - D_{\mathrm{e,i,m}} \vec{\nabla} n_{\mathrm{e,i,m}},$$

$$\frac{\partial n_{\mathrm{e}} T_{\mathrm{e}}}{\partial t} = -\vec{\nabla} \cdot (\frac{5}{3} T_{\mathrm{e}} \vec{\Gamma}_{\mathrm{e}} - \frac{5}{3} n_{\mathrm{e}} D_{\mathrm{e}} \vec{\nabla} T_{\mathrm{e}}) - e\vec{\Gamma}_{\mathrm{e}} \cdot \vec{E} - n_{\mathrm{e}} n_{\mathrm{G}} k_{\mathrm{loss}},$$

and

$$T_{\mathrm{i}} = T_{\mathrm{m}} = 0.026\ eV.$$

Fluid Models

Ar atomic processes considered in the simulation

Equation of Reaction	Rate of Reaction Coefficient	
$e + Ar \rightarrow Ar^{+} + 2e$	impact-ionization	$K_{ei} = 1.253 \times 10^{-7} \exp(-18.618/T_e)\ cm^3/s$
$e + Ar \rightarrow Ar^{*} + e$	collisional-excitation	$Kex = 3.712 \times 10^{-8} \exp(-15.06/T_e)\ cm^3/s$
$e + Ar^{*} \rightarrow Ar^{+} + 2e$	impact-ionization	$K_{mi} = 2.05 \times 10^{-7} \exp(-4.95/T_e)\ cm^3/s$
$e + Ar^{*} \rightarrow Ar + e$	collisional-deexcitation	$K_{em} = 1.818 \times 10^{-9} \exp(-2.14/T_e)\ cm^3/s$
$e + Ar^{*} \rightarrow Ar^{r} + e$	radiative-deexcitation	$K_r = 2 \times 10^{-7}\ cm^3/s$
$Ar^{*} + Ar^{*} \rightarrow Ar^{+} + Ar + e$	collisional-ionization	$K_{mm} = 6.2 \times 10^{-10}\ cm^3/s$
$Ar^{*} + Ar \rightarrow 2Ar$	collisional-deexcitation	$K_{2q} = 3.0 \times 10^{-15}\ cm^3/s$
$Ar^{*} + 2Ar \rightarrow Ar + Ar_2$	attachment	$K_{3q} = 1.1 \times 10^{-31}\ cm^6/s$

Main reactions and the corresponding rate coefficients in the Ar/CF_4 discharge plasma.

Reaction equation	Reaction rate coefficient
$CF_3^- + Ar^+ \rightarrow CF_3 + Ar$	1×10^{-7} cm^3 s^{-1}
$F^- + Ar^+ \rightarrow F + Ar$	1×10^{-7} cm^3 s^{-1}
$CF_4 + Ar^+ \rightarrow CF_3^+ + F + Ar$	9.58×10^{-10} cm^3 s^{-1}
$Ar + CF_3^+ \rightarrow CF_3 + Ar^+$	1×10^{-9} cm^3 s^{-1}

Chengjie Bai *et al* 2018 *J. Phys. D: Appl. Phys.* 51 255201

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Main reactions and the corresponding reaction rate coefficients in the CF_4 discharge plasma.

Reaction equation	Reaction rate coefficient
$CF_4 + e \rightarrow CF_4^+ + 2e$	Calculated by BOLSIG+
$CF_3 + e \rightarrow CF_3^+ + 2e$	$1.4 \times 10^{-11}(11\,605 \times T_e)^{0.6481}\exp(-9.8/T_e)$ cm^3 s^{-1}
$F + e \rightarrow F^+ + 2e$	$7.489 \times 10^{-13}(11\,605 \times T_e)^{0.8595}\exp(-17.6/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_4^*(12.5\,eV) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_4^*(8\,eV) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_4(V13) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_4(V24) + e$	Calculated by BOLSIG+
$CF_4 + e \rightarrow CF_3^+ + F + 2e$	$1.159 \times 10^{-11}(11\,605 \times T_e)^{0.7645}\exp(-17.2/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_2^+ + F_2 + 2e$	$2.886 \times 10^{-11}(11\,605 \times T_e)^{0.5108}\exp(-22.8/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF^+ + F_2 + F + 2e$	$2.296 \times 10^{-14}(11\,605 \times T_e)^{1.09}\exp(-27.0/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_3 + F^+ + 2e$	$1.482 \times 10^{-13}(11\,605 \times T_e)^{0.9375}\exp(-34.7/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_3 + F + e$	$2 \times 10^{-9}\exp(-13/T_e)$ cm^3 s^{-1}
$CF_4 + e \rightarrow CF_2 + 2F + e$	$5 \times 10^{-9}\exp(-13/T_e)$ cm^3 s^{-1}
$CF_3 + F^- \rightarrow CF_4 + e$	5×10^{-10} cm^3 s^{-1}
$CF_2 + F^- \rightarrow CF_3 + e$	5×10^{-10} cm^3 s^{-1}
$CF + F^- \rightarrow CF_2 + e$	5×10^{-10} cm^3 s^{-1}
$CF_3 + F \rightarrow CF_4$	2×10^{-11} cm^3 s^{-1}
$CF_2 + F \rightarrow CF_3$	1.3×10^{-11} cm^3 s^{-1}
$CF + F \rightarrow CF_2$	5.2×10^{-15} cm^3 s^{-1}
$CF_3^- + CF_3^+ \rightarrow 2CF_3$	4×10^{-7} cm^3 s^{-1}
$F^- + CF_3^+ \rightarrow F + CF_3$	4×10^{-7} cm^3 s^{-1}
$F^- + CF_2^+ \rightarrow F + CF_2$	$1 \times 10^{-7}T_g^{-0.5}$ cm^3 s^{-1}
$F^- + CF^+ \rightarrow F + CF$	$1 \times 10^{-7}T_g^{-0.5}$ cm^3 s^{-1}
$F^- + F^+ \rightarrow F_2$	$4 \times 10^{-7}T_g^{-0.5}$ cm^3 s^{-1}
$CF_2^+ + e \rightarrow CF + F$	4×10^{-8} cm^3 s^{-1}
$CF^+ + e \rightarrow C + F$	4×10^{-8} cm^3 s^{-1}
$CF_3^+ + e \rightarrow CF_3$	9.6×10^{-7} cm^3 s^{-1}
$F^+ + e \rightarrow F$	4×10^{-8} cm^3 s^{-1}
$CF_4^+ \rightarrow CF_3^+ + F$	3.3×10^5 s^{-1}
$CF_4 + e \rightarrow CF_3 + F^-$	4.8×10^{-12} cm^3 s^{-1}
$CF_4 + e \rightarrow CF_3^- + F$	3.28×10^{-11} cm^3 s^{-1}
$CF_2 + F_2 \rightarrow CF_3 + F$	4.56×10^{-13} cm^3 s^{-1}
$CF_3 + F_2 \rightarrow CF_4 + F$	1.88×10^{-14} cm^3 s^{-1}
$CF_3^- + F \rightarrow CF_3 + F^-$	5×10^{-8} cm^3 s^{-1}
$2CF_4^*(12.5\,eV) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}
$2CF_4^*(8\,eV) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}
$2CF_4(V13) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}
$2CF_4(V24) \rightarrow 2CF_4$	4.9×10^{-4} cm^3 s^{-1}

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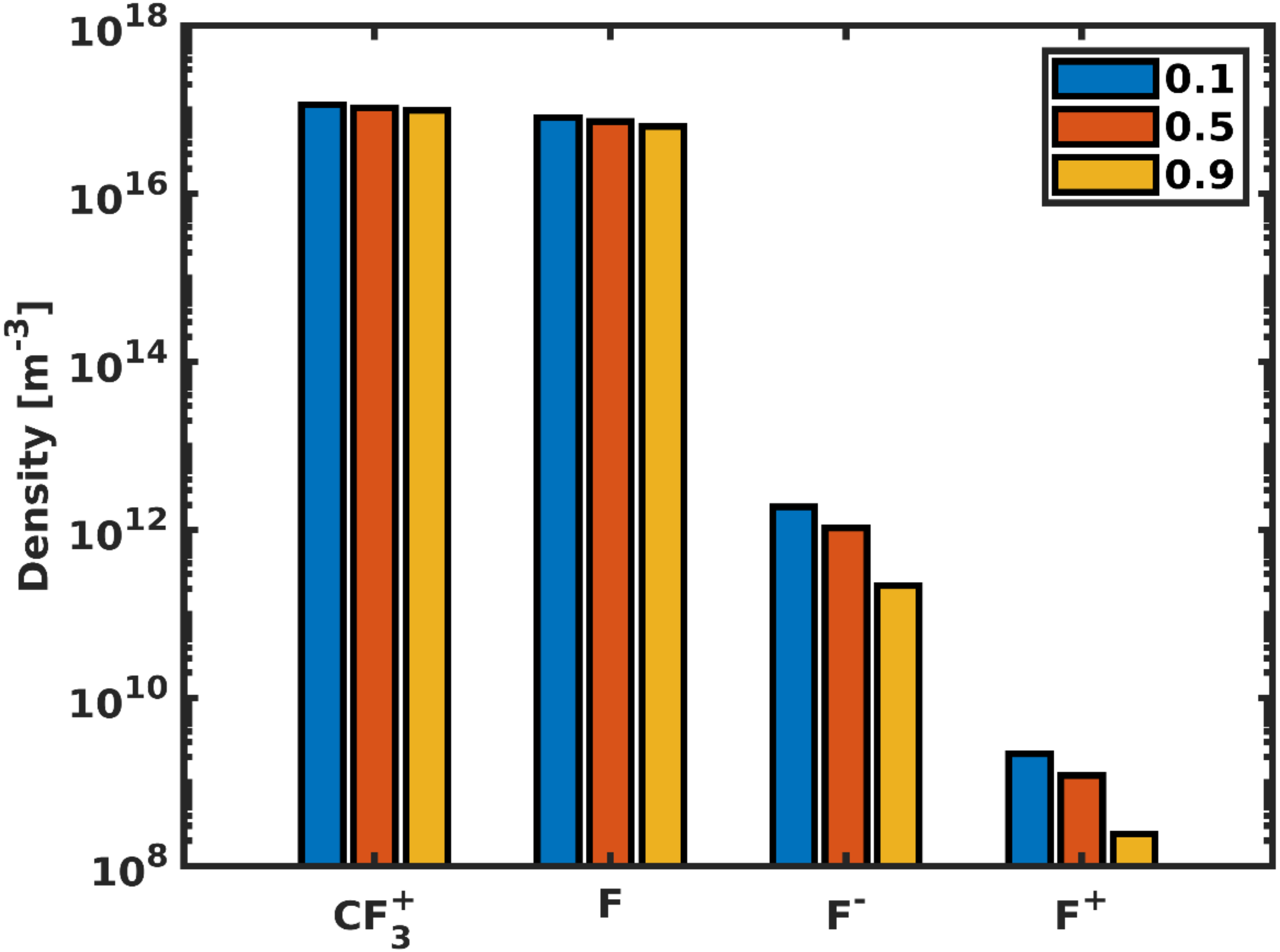
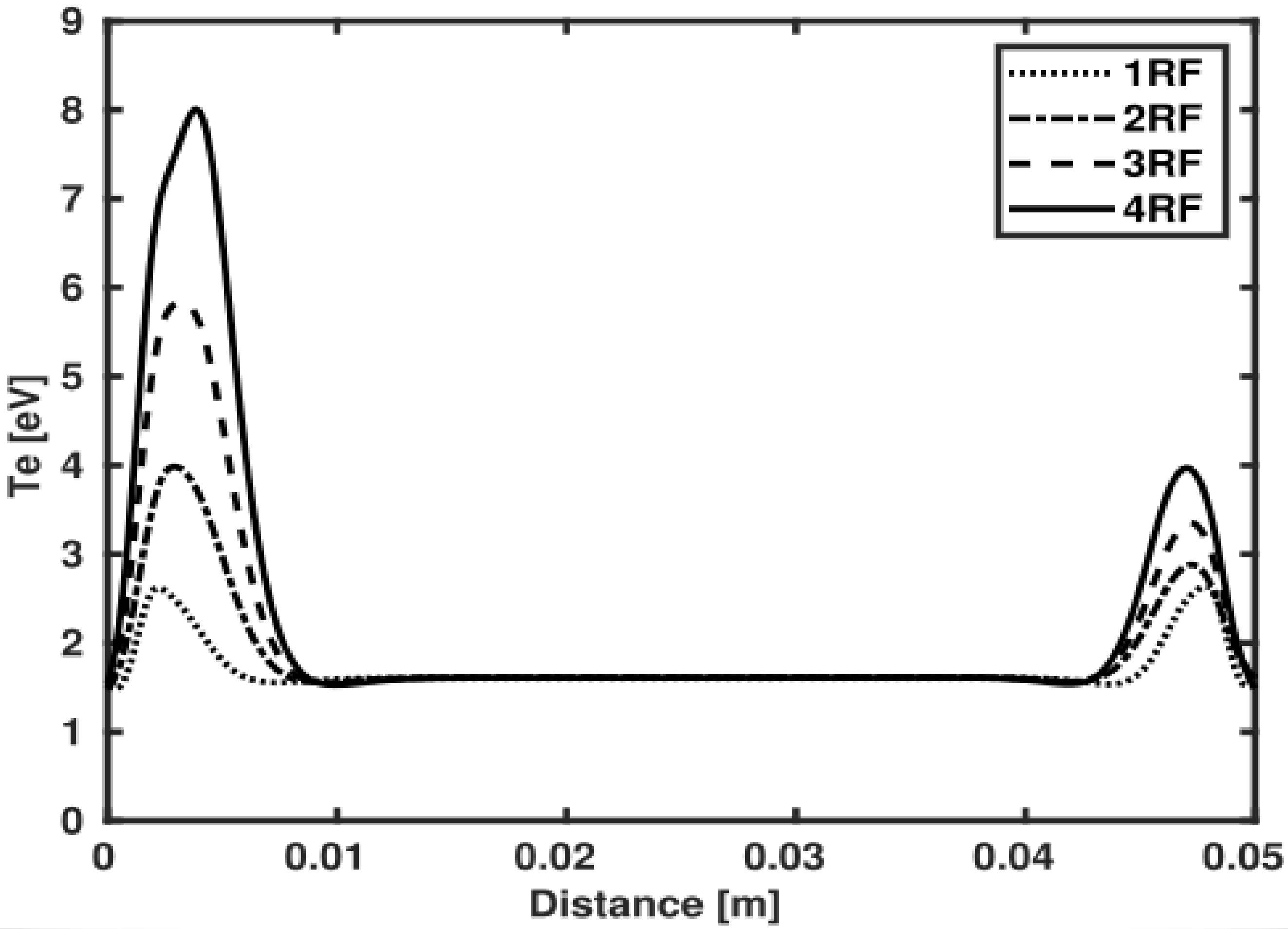
The effect of Ar ratios



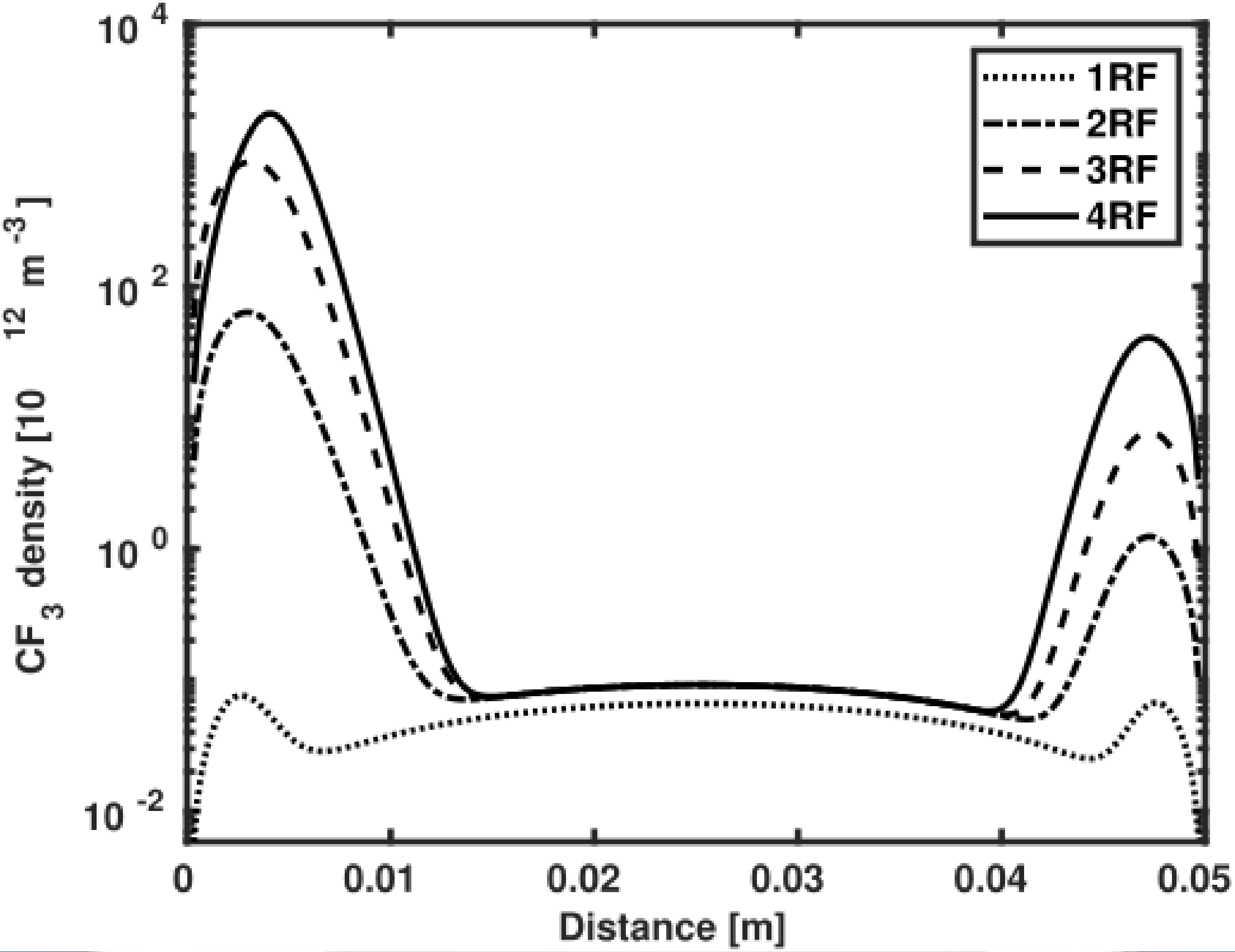
The electron temperature

Fundamental frequency=13.56MHz

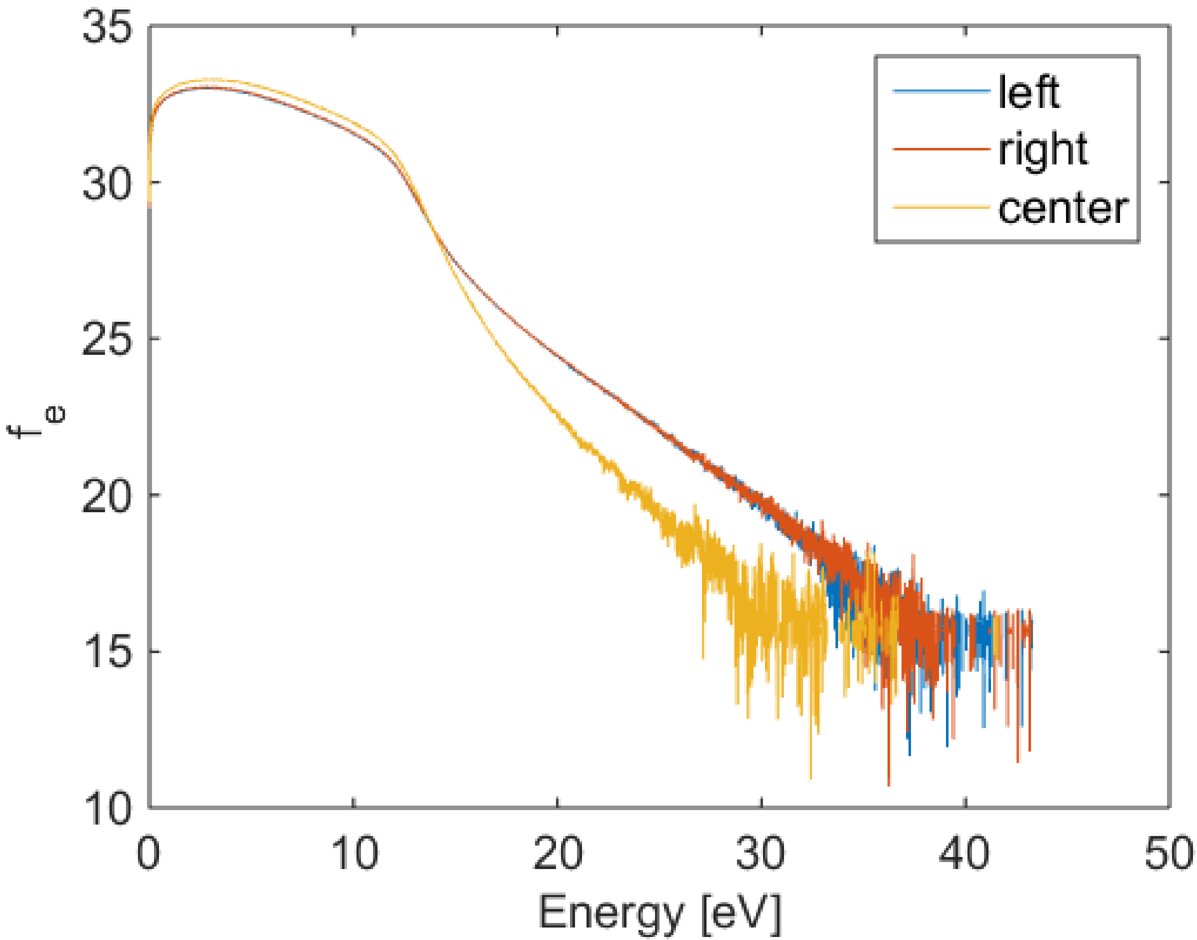


The density of CF3 Species

Fundamental frequency=13.56MHz



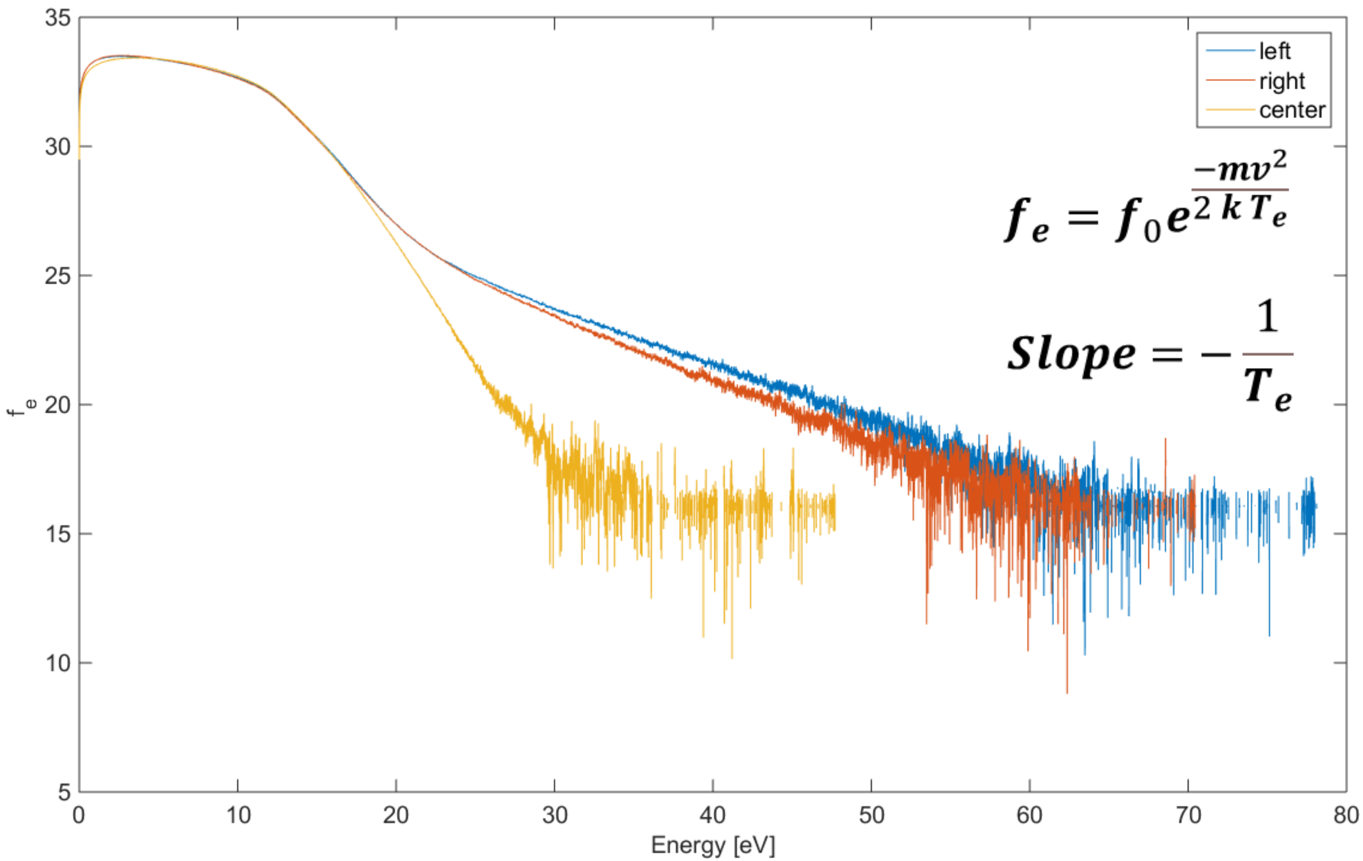
Kinetic Confirmation-Symmetric discharge



$$f_e = f_0 e^{\frac{-mv^2}{2\,k\,T_e}}$$

$$Slope = -\frac{1}{T_e}$$

Kinetic Confirmation-Asymmetric discharge



Thanks!

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